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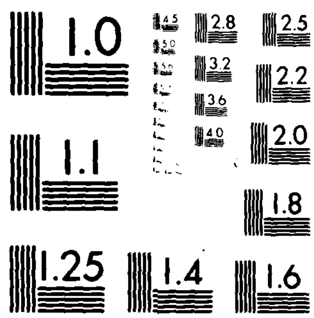

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

Report No. FAA-RD-80-120

LEVEL II

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AD A094169

EVALUATION OF THE PERFORMANCE OF THE REMOTE AREA PRECISION POSITIONING SYSTEM (RAPPS)

E. H. Bolz

T. E. Scalise

October 1980

Final Report

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Prepared for

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16. Abstract

A flight test program was flown within the coverage area of the West Coast Loran-C chain during June and July 1979. These tests were conducted for Loran-C evaluation purposes. The Remote Area Precision Positioning System (RAPPS) was utilized as the data collector and independent positioning system for those tests. This report presents an evaluation of the performance of the RAPPS system under actual test conditions.

The RAPPS positioning system is based on DME multilateration and takes advantage of existing TACAN or DME installations. It was found under certain conditions to suffer degradation due to multipath propagation and signal dropouts due to terrain masking. After isolating clearly erroneous measurements, residual ranging errors of 285 ft (1σ) were estimated based on available data.

The RAPPS data collector was designed to acquire data from two Loran-C receivers, the DME subsystem, an altimeter and a clock. The data collector functioned satisfactorily with a few deficiencies. The foremost deficiency was a lack of precise time-tagging of each individual data element, which caused processing of the Loran-C data to be quite difficult.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

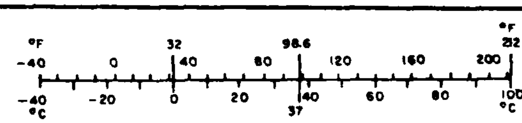


TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF TABLES

LIST OF FIGURES

1.0 EXECUTIVE SUMMARY

In the summer of 1979 a series of tests of a Loran-C navigator were flown utilizing the recently-commissioned West Coast Loran-C chain. The Remote Area Precision Positioning System(RAPPS) was used as the ground-truth position reference and data collector for those tests. An analysis of the performance of the navigator and the Loran-C chain is contained in Reference 1. This companion report analyzes the the performance of the RAPPS during those tests.

1.1 INTRODUCTION

The RAPPS was designed to be a complete positioning and data collection system for supporting the test of navigation systems and approach aids. It was configured as of June 1979 to instrument two Loran-C receivers: the Teledyne TDL-424 and the Teledyne TDL-711. During the test the 424 was on loan and so only the 711 was evaluated. RAPPS functioning is based on an Intel System 80 microcomputer, which handles all interfacing and data formatting chores. The independent positioning capability is provided by a modified King KDM-7000 DME set which was interfaced to a *cycling channel programmer.* This device sequences the DME through six different TACAN channels at the rate of one per second. In the one second period the DME will acquire the range to a beacon, which is then communicated to the computer. The computer assembles the data collected from the DME system, the two Loran-C navigators, an altimeter and a digital clock, and formats the data into a record written onto magnetic tape.

Proper functioning of the RAPPS positioning subsystem depends on the existence of DME beacons in the area of interest for the test. These may be existing VORTAC, VOR/DME or ILS/DME installations. There also may be temporary beacons installed for purposes of the specific test. During the West Coast tests three different types of portable beacons were used (in addition to existing fixed facilities): Butler 1066 and 1020 DME ground station transponders and Vega 316L transponders. Care must be exercised to ensure that the flight path of the aircraft will be adequately covered by available beacons. Several criteria should be met. For example, at the very least two beacons should be receivable

at all times, which can be problematic since coverage can be limited both by range and line-of-sight considerations. Also, the geometry of the aircraft relative to the available beacons is critical to the realization of the potential accuracy of the positioning system.

This report presents an analysis of the performance of RAPPS as a flight test data collector and as a precision positioning system. The evaluation covers accuracy as well as other performance aspects of the positioning system. Data collector performance and problems, and system operator interactions are evaluated.

1.2 SUMMARY OF RESULTS

The performance of the RAPPS positioning system was evaluated in the following ways:

1) Reply Efficiency: The ability of the system to consistently elicit and track replies from each beacon in the coverage area.
2) Gross Range Measurement Errors: A count of occurrences of large errors in range measurement.
3) Multipath Range Measurement Errors: A count of occurrences of smaller significant range measurement errors, probably resulting from multipath propagation effects.
4) Residual Range Measurement Errors: A statistical analysis of the range measurement errors other than those described above.

The reply efficiency results are presented graphically in Section 4.3. Briefly, the findings are as follows. In general, two factors were found to have a very strong influence on reply efficiency. First, line-of-sight restrictions were encountered which can be classed in two categories. The first were clear-cut line-of-sight limitations which resulted from the presence of intervening mountainous terrain. These were fully expected, particularly in view of the rough terrain chosen for these tests. The second was experienced in cases where the beacon was located only 3 to 5 miles away from the aircraft in even or gently rolling terrain. As the aircraft descended on final approach, signals from these beacons were routinely lost.

In Table 1.1 the results of the ranging system error analysis are presented. Results for individual beacons are presented graphically and in tabular form in Section 4.3. Gross ranging errors were identified in 16 out of the 6085 data points recovered, or at a rate of 0.25%. Gross errors are relatively easy to spot and eliminate from the data reduction process when the RAPPS is utilized as the position standard for a flight test. Smaller significant ranging errors (probably due to multipath propagation) were identified in one hundred of the remaining 6069 data points. These errors, by definition greater than 1000 feet and typically on the order of 1500-2500 feet, are much more difficult to identify and expunge when utilizing the RAPPS data as a position standard. Therefore, they tend to contaminate the results. Analyses of the remaining 5969 data points resulted in a mean computed ranging error of -23 feet with a standard deviation of 285 feet. These values represent raw ranging accuracies and are not directly translatable into positioning accuracy. Positioning errors could be larger or smaller in any given instance depending on beacon geometry and the number of available beacons. Since this ranging error analysis was performed without benefit of an independent absolute position standard, the resulting standard deviation value is probably conservative (greater than actual performance).

Table 1.1 RAPPS Beacon Performance Summary

LOCATION	RECOVERED DATA POINTS	GROSS RANGE ERRORS (POINTS)	MULTIPATH ERRORS (POINTS)	RESIDUAL ERRORS (FEET)	
				MEAN	SD
South Lake Tahoe	2893	11	75	35'	299'
Grand Junction	549	0	3	32'	207'
Klamath Falls	2643	5	22	-96'	268'
TOTAL	6085	16	100	-23'	285'

The above results apply in general to all the tests flown as a part of this program. Events experienced during flights at South Lake Tahoe deserve special mention. In those flights the reply efficiency from one of the beacons (located at the airport) was very poor, and the multipath

error rate detected was very high. These errors occurred even though that beacon was operating properly and was in clear line-of-sight of the aircraft at all times. The probable cause identified stemmed from the fact that this beacon was located near the lake and virtually at lake elevation, and that the lake was quite smooth during the tests. It is believed that multipath propagation with the lake as reflector occurred resulting in significant periods of signal cancellation. False lock-on to erroneous ranges occurred often as signals reflected from the nearly mountains.

The beacon placement procedures employed during the test were evaluated critically. While virtually every beacon placement performed could be viewed as a significant learning opportunity, two major conclusions result from that study. First, knowledge of the absolute location of a beacon is extremely important. This is difficult to achieve in the field. Second, during all parts of the flight path (of interest), a bare minimum of two and preferrably three should be in clear line-of-sight view of the aircraft. In practice the second principle is often sacrificed for the first; i.e., locations are chosen which are easy to get to and are accurately known. Only after the test has been completed is it realized that the beacon cannot be reliably received. Beacons located at high elevations provide best overall performance.

In Section 5 the performance of RAPPS as a flight test data collector is evaluated in detail. In general the system performed well and provided usable data. Some performance quirks were noted which apparently resulted from programming errors or improper program design; however, these flights constituted the first airborne testing of RAPPS, and so software problems are not to be unexpected. The major deficiency of the data collector was the lack of precise time annotation of all data fields. Due to the unexpected performance characteristics of the Loran-C navigator, it was difficult to ascertain the age of the Loran-C data recorded, which renders error analysis rather difficult.

The system required a trained technician for its operation. While operation of RAPPS is not laborious, proper operation required detailed knowledge of the systems which comprise RAPPS. Control of the data collector was exercised through a graphic terminal. That terminal was also programmed to serve as a real time position display system. That capability was not evaluated during these tests.

2.0 BACKGROUND

The evaluation contained in this report evolved from data and experience gained through the use of the Remote Area Precision Positioning System (RAPPS) during the Loran-C West Coast Test Program. What follows in this section is a discussion of the purpose of RAPPS and a brief description of the West Coast Loran-C tests for which it was used.

2.1 PURPOSE OF THE REMOTE AREA PRECISION POSITIONING SYSTEM (RAPPS)

In any test of the accuracy of an air navigation system, whether enroute or terminal, an essential element of that test is a means to fix the test aircraft position independently from the system being tested. It was for just such a purpose that RAPPS was used during flight tests of Loran-C as a non-precision approach aid, using the West Coast Loran-C Chain.

The RAPPS itself is a positioning system that can record range from up to six DME beacons by cyclically polling those beacons in flight. The ranging information from these beacons is then fed into a microprocessor, combined with baro-uncorrected altitude, and then time-tagged to produce the data necessary to arrive at an aircraft position using multilateration techniques.

During the West Coast Loran-C test the RAPPS was used to fix aircraft position using a mixture of fixed DME beacons (ILS/DME, VOR/DME, VORTAC) and uniquely positioned portable DME beacons. The position information it provided was then compared with Loran-C positioning data during post-test analysis, and served as a criterion against which the Loran-C system accuracy could be measured.

The West Coast test applications of the RAPPS emphasize its major advantage over other ground truth systems - that of range portability. As long as beacons can be placed appropriately, no matter the remoteness of the site, a precision range can be set up. It was just such flexibility that allowed ground truth data to be collected in areas where no other accurate system was available and in the kind of rugged terrain required by the West Coast Loran-C test objectives.

2.2 THE LORAN-C WEST COAST TEST PROGRAM

The Loran-C Flight Test Program [1] flown using the West Coast Loran-C Chain was designed to analyze the performance of both the Loran-C Chain itself and the airborne Loran-C micro-navigator system in a series of varied scenarios. The test profiles and locations were selected to provide an extensive mix of terrain, geometry, and positioning conditions within the context of an actual operational environment.

In the midst of this demanding program the suitability of Loran-C as a non-precision approach aid was also tested. The non-precision approaches flown at five locations (South Lake Tahoe, California; Klamath Falls, Oregon; Grand Junction, Colorado; Reno, Nevada, and Reno/Stead, Nevada) became the framework within which data were collected for an analysis of both Loran-C reliability and accuracy, and an operational assessment of the Loran-C ground and airborne systems.

An important part of that analysis was a computation of Loran-C position accuracy and the effects on that accuracy of Loran-C bias, signal propagation characteristics, and positioning geometry. The Remote Area Precision Positioning System developed by the Sierra Nevada Corporation was used as a ground truth system to provide an independent method of fixing aircraft position against which the Loran-C system could be compared.

Of the five locations at which flight tests were flown, three were formal test approach locations: Lake Tahoe, Klamath Falls, and Grand Junction. The flights at the Reno International and Reno/Stead airports were system checkout missions, although data were recorded during these missions also and they contributed to the overall assessment of the Loran-C system. The next sections contain a description of the methods by which the RAPPS was employed in its ground truth role.

2.2.1 South Lake Tahoe, California

Lake Tahoe Airport is located on the south shore of Lake Tahoe. The lake itself, and the airport, are ringed with high terrain in all quadrants. The test approach was designed to be flown straight-in to Runway 18. Figure 2.1 shows the Lake Tahoe test location and approach

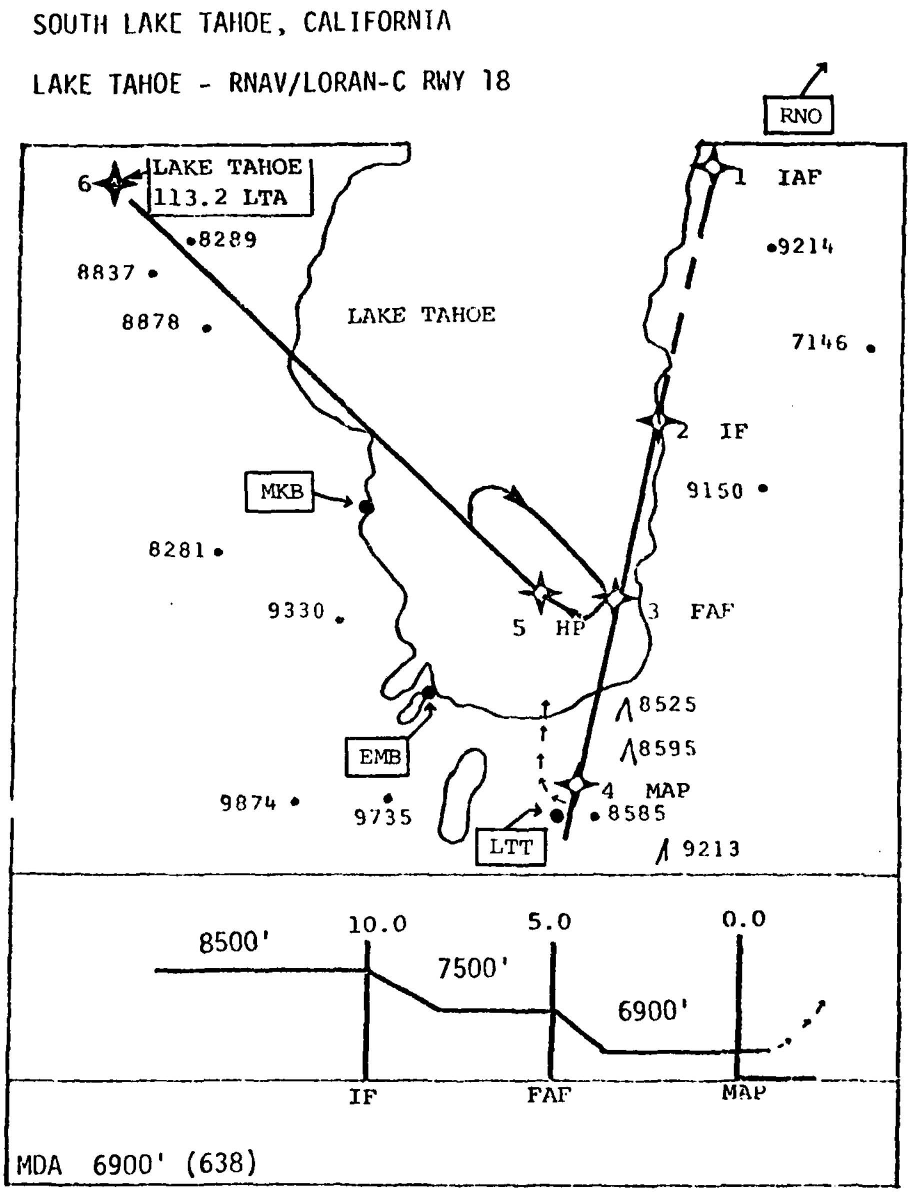


Figure 2.1 Test Approach and Beacon Configuration at Lake Tahoe

as well as the location of the beacons (both fixed and portable). LTA is the fixed TACAN station co-located with the Lake Tahoe VOR. RNO is the DME beacon of the Reno VORTAC. LTT is a portable Butler 1066 DME beacon placed near the Lake Tahoe tower. MKB is the portable Butler 1066 DME beacon located at a roadside location on a cliff overlooking Meeks Bay on the central western shore of the Lake. EMB is a Vega 316L beacon (L-Band) located near Emerald Bay on the southwestern shore of Lake Tahoe.

For the first five test approaches, all the above beacons but EMB were used. The EMB beacon was available only for the last five approaches, since it was installed after the flights were initiated.

2.2.2 Klamath Falls, Oregon

The test approach to Kingsley Field was to Runway 32. Three beacons (shown in Figure 2.2) were used for ground truth multilateration at Klamath: STM, a Butler 1066 beacon placed near an antenna farm on top of Stukel Mountain; another Butler 1066, designated SPL, located on a private farm near Spring Lake; and, LMT, the TACAN co-located with the VOR on the field at Kingsley. Terrain was such that good reception of all the beacons was possible throughout the six test approaches flown there.

2.2.3 Grand Junction, Colorado

Walker Field lies in the River Valley at the junction of the Colorado and Gunnison Rivers. Within a few miles of the field the terrain rises abruptly to 7000' (southwest) and 8000' (northeast). Three DME beacons were used by the RAPPS for the Grand Junction approaches (see Figure 2.3). GJT is the TACAN co-located with the Grand Junction VOR on the 7000' mesa west of the field. A Butler 1066 beacon, designated FIR, was installed near the fire station on the airport. A Vega 316L beacon, called PER, was located on the roof of a private dwelling situated southwest of the final approach course to Runway 11.

KLAMATH FALLS, OREGON

KINGSLEY - RNAV/LORAN-C RWY 32

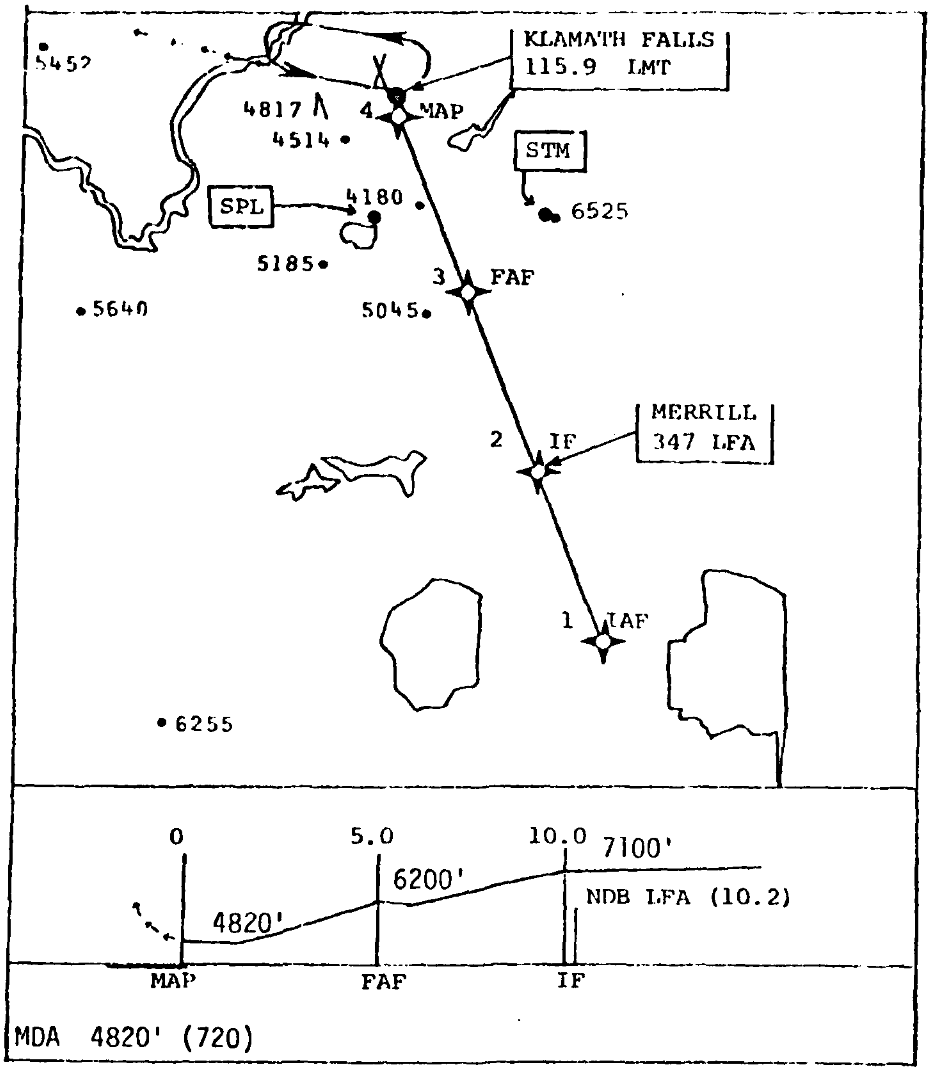


Figure 2.2 Test Approach and Beacon Configuration at Klamath Falls

GRAND JUNCTION, COLORADO

WALKER FIELD - RNAV/LORAN-C RWY 11

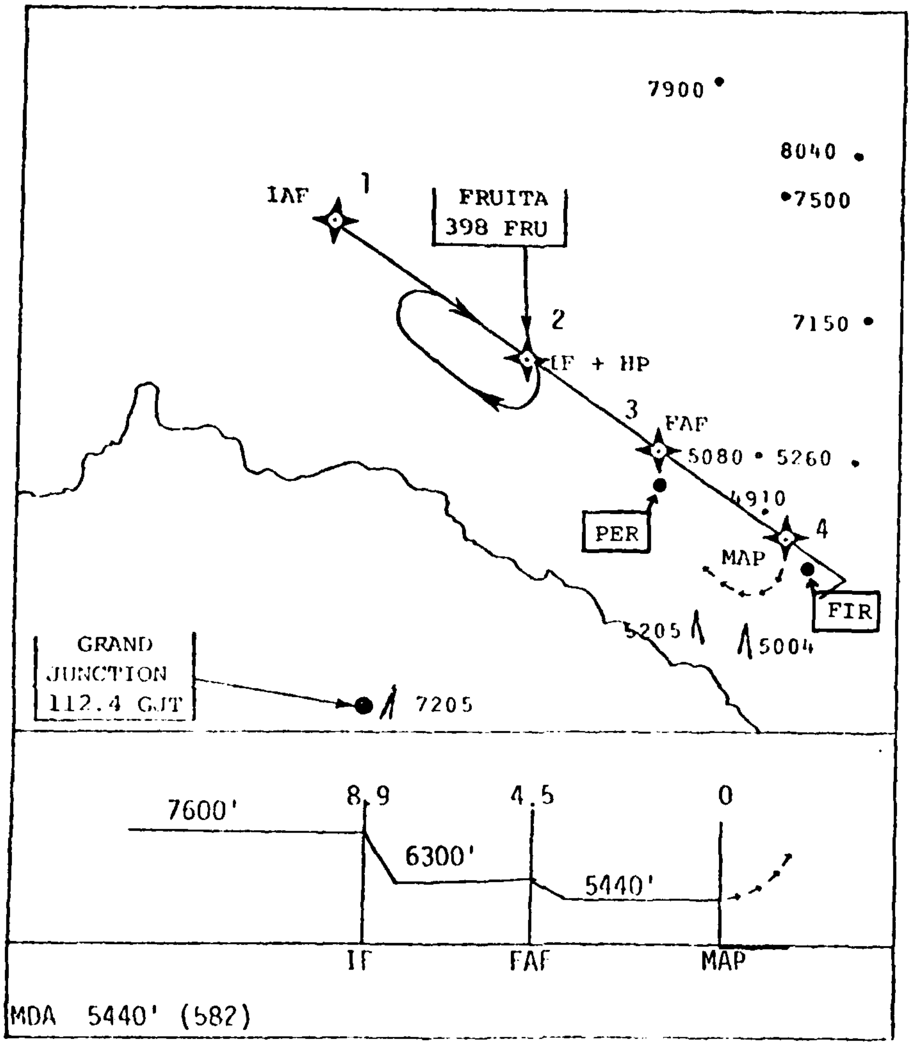


Figure 2.3 Test Approach and Beacon Configuration at Grand Junction

2.2.4 Reno, Nevada

The Reno International Airport lies in a valley surrounded by foothills. Instrument approaches are conducted to runway 16, as illustrated in Figure 2.4. The beacons utilized were the Reno VORTAC (RNO), the Reno ILS DME (IRN), a Butler beacon located at Stead airport (SNC) and a Butler beacon located on Peavine mountain (PVN).

2.2.5 Reno/Stead, Nevada

The Stead airport (former Air Force base) is located northwest of Reno International. There are no instrument approaches commissioned for Stead airport. The test approaches were conducted to runway 26. The Reno VORTAC (RNO) was used, as was a Butler beacon located just south of the runway (SNC). The beacon location on Peavine mountain (PVN) was utilized, as well as a Vega beacon installed on a rooftop southwest of the airport (DRI).

2.2.6 Overall Loran-C Geometry

Each of the five above locations are noted on a chart of the entire West Coast Loran-C chain. This chart, Figure 2.5, also shows the nominal coverage areas of that chain.

RENO, NEVADA

RENO INTERNATIONAL - RNAV/LORAN-C RWY 16

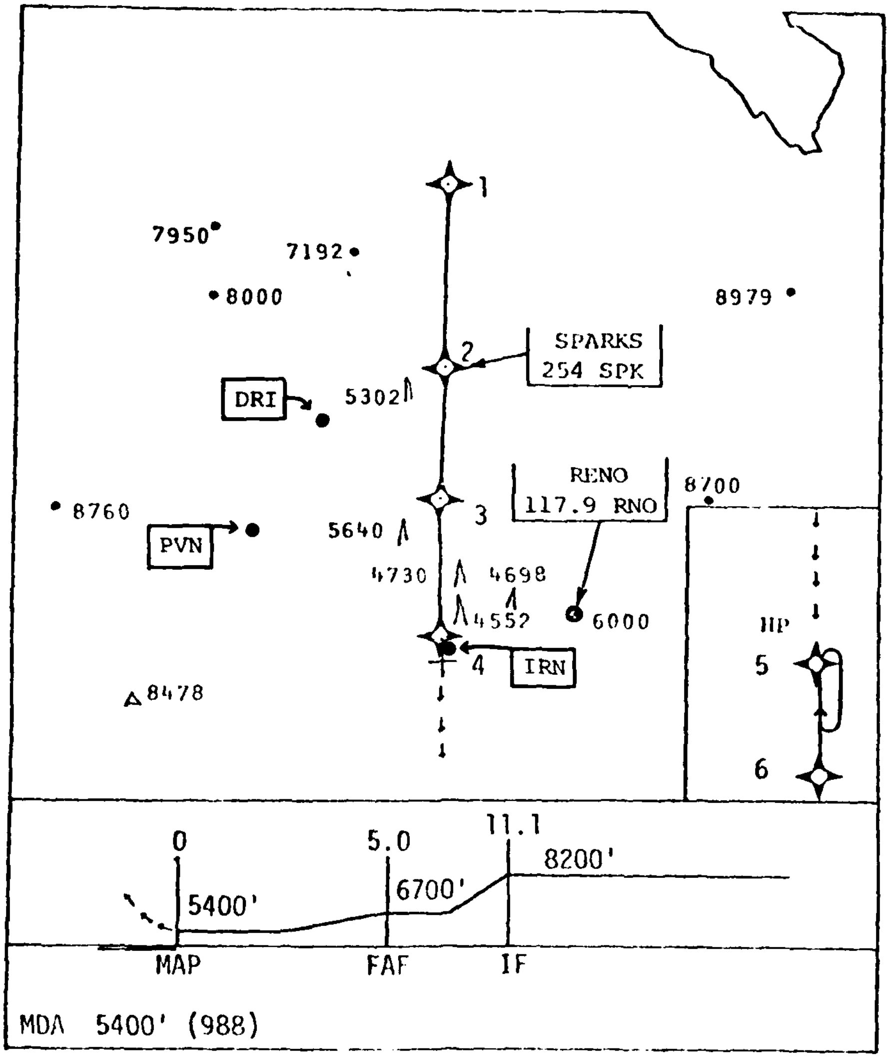


Figure 2.4 Test Approach and Beacon Configuration at Reno

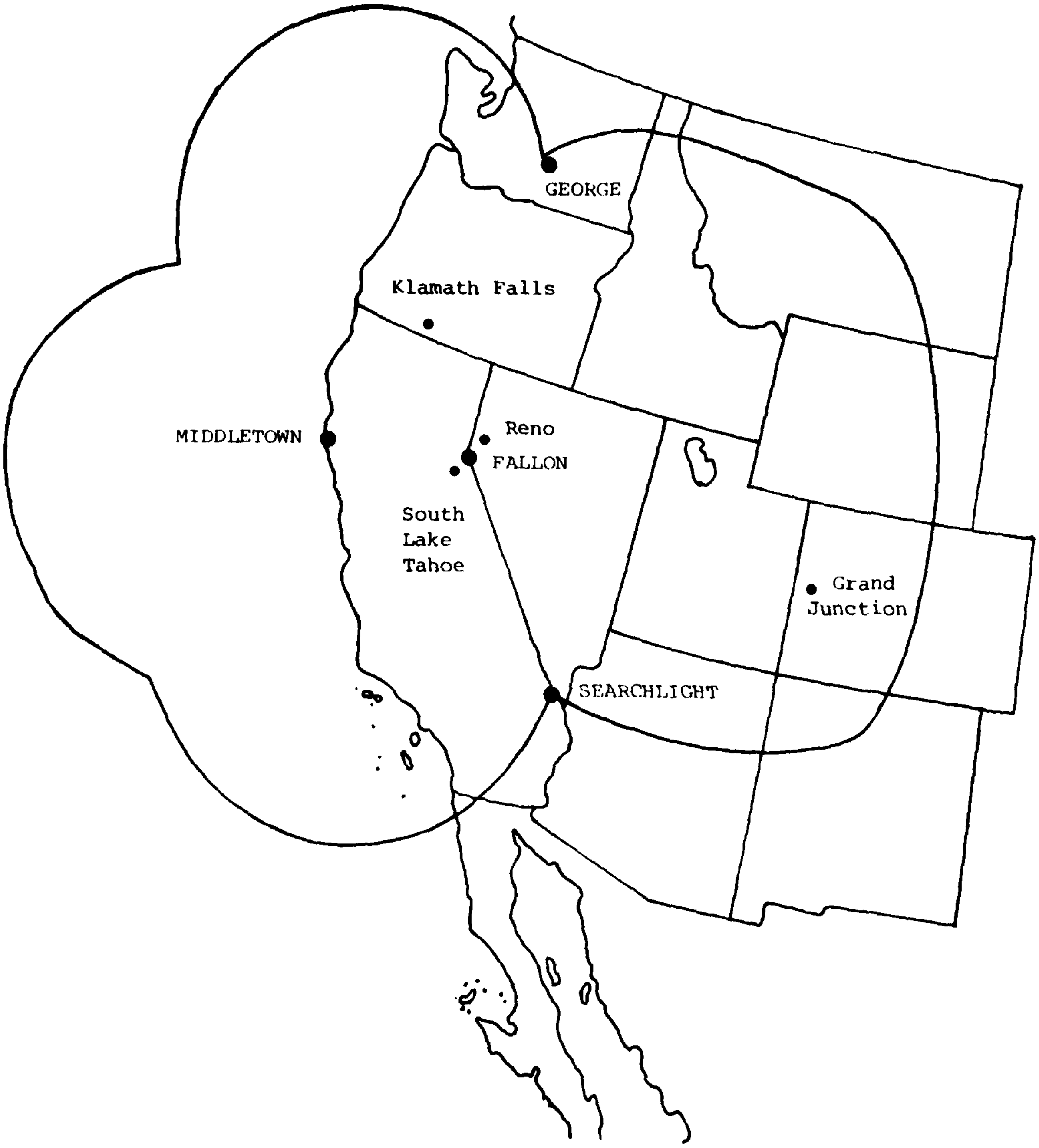


Figure 2.5 The West Coast Loran-C Chain Coverage

3.0 FUNCTIONAL DESCRIPTION OF RAPPS

The discussion in this section will focus on the three major subsystems of RAPPS. They are the ranging system, the data collector, and the real-time display. The section will conclude with a description of the physical characteristics of the RAPPS.

3.1 THE RANGING SYSTEM

There are two, mutually interactive components in the RAPPS ranging system [2]. First is the airborne component, consisting of an Intel 80/20-4 microprocessor which controls the tuning of a King KDM-7000 DME transponder-interrogator and cycles the KDM-7000 among as many as six DME beacons, whose frequencies are entered using a bank of thumbwheel selectors. Second is the ground component, consisting of existing FAA DME beacons (e.g. VORTACs, ILS/DMEs) and a variable number of portable transponders placed at known locations.

When the real time position display feature is used, the exact latitude and longitude of each beacon must be entered in the memory of the Tektronix 4051 intelligent terminal. Multilateration techniques are then used to fix the position of the aircraft.

As the system cycles through the ground transponders in use, it pauses for one second at each to record range data, for a total of six seconds per full cycle. The perceived range to a ground transponder is a function of the time required for a transmission from the interrogator to reach the ground beacon and return from that beacon to the aircraft interrogator. That round trip time is compared to the known round trip time of radio signals over a measured distance (e.g. a radio signal will traverse a one mile distance round trip in 12.36 microseconds). The following sections will explore the ground and airborne elements of the ranging system in greater detail.

3.1.1 The Ground Transponders

As soon as a typical DME ground transponder is powered up, it begins to produce a constant level of pulsed transmissions at its

unique transmission frequency. If no interrogator pulse pairs are being received, the beacon reacts to the general noise level in the radio environment at its unique reception frequency, adjusting its receiver gain until its transmitter is triggered 2700 times per second. This random return of noise-triggered pulse pairs is called "squitter". If the noise level should fall or rise enough for the pulse rate to change from 2700 pulse pairs per second (PPPS), the gain is increased or decreased accordingly to maintain that rate. When an interrogator pulse pair is received, a timer is started to effect a delay of 50 μsec. The pulse pair is then transmitted on the transmission frequency.

Typically, ground transponders can service at least 50 different interrogators simultaneously and often service 100 at any given time. When the number of interrogators increases to 100, a point is reached where the number of reply pulses transmitted produce a 2700 PPPS rate. At that point "squitter" is non-existent. Any additional interrogators would produce a rate higher than 2700, and as this begins to occur the ground station receiver gain would be reduced until the 2700 PPPS rate was regained. In effect, those interrogators farthest away from the ground station or with the lowest transmission power would be ignored until the total number of interrogators dropped below 100, at which time the reply pulse rate would fall below 2700 PPPS. The receiver gain would then be increased until some of the ignored beacons would again be included and the reply pulse rate stabilized at 2700 PPPS. Under normal conditons, however, complete saturation by interrogators is unlikely and some "squitter" would be present to keep the reply rate at 2700 PPPS.

There are three kinds of ground beacons used by the RAPPS. First is the FAA DME beacon co-located with a radio navigation aid (e.g. VORTAC, ILS-DME). Second is a portable beacon, in this case either a Butler 1066 or a Butler 1020. Third is the Vega 316L. The FAA beacons operate as already described, except that for 3 seconds of every 30 seconds, a station identification is broadcast. This, coupled with TACAN reference pulses (if part of a VORTAC) and replies to other

aircraft, creates a reply efficiency of 70% to 80%.. In other words, a given interrogator can expect replies to 70% or 80% of its transmitted pulse pairs. The Butler beacons have lower "squitter" rates (1000 PPPS) and no identity transmission. The Vega beacons broadcast no squitter and no identity transmissions.

3.1.2 The Airborne Interrogator

The airborne interrogator transmits pulse pairs on a frequency corresponding to the reception frequency of the selected ground transponder. The pulses are received by the ground station, delayed exactly 50 μsec, and returned to the interrogator at its reception frequency (63 MHZ above or below its transmit frequency).

When operating, the interrogator is in one of two modes: search or track. In the search mode it scans through the pulses it has received until it recognizes the replies to its own transmitted pulses. It then ignores the other pulses. The interrogator can recognize its "own" pulses because during each transmission it introduces a randomly changing delay between pulses. It then waits 50 μsec, and, starting at a time corresponding to zero miles range, begins to look for pulses with that same random separation. If no replies appear in this range "gate", it moves the gate outward in one mile increments until a pulse pair with the current random separation appears in the gate. It then waits until it has found 10 successive pulse pairs in that range gate, assuring that the signals are valid. During this search operation, the interrogator will be transmitting roughly 150 pulse pairs per second (PPPS). When a valid signal is acquired, the track mode is entered.

Typically, in the track mode the interrogator reduces its transmission rate to between 5 and 25 PPPS. This significant reduction in pulse pair frequency, coupled with the likelihood that most of the interrogators tuned to a given ground transponder are in this reduced transmission (track) mode, is what makes it possible for a ground station to service up to 100 interrogators simultaneously.

To prevent periodic return to search mode during ground station identification periods and during transient loss of valid signals in

the range gate, the gate can use data stored in memory to continue at its last movement rate or remain static (depending on manufacturer and model). This coasting capability lasts for about 10 seconds, typically, before the range gate is returned to zero miles and the search begins again for a valid signal.

The time necessary to acquire a valid signal is a function of "squitter" generation rates and maximum range. The KDM-7000 looks at its first received signal and determines if it is valid by noting whether a valid signal has been acquired, that is ten replies have appeared in the range gate before four consecutive "squitter" pulse pairs have been received. If the signal is not valid, the range gate is moved successively outward. The farther away the ground station is, the longer the scan until valid pulse-pair replies appear.

With VORTAC beacons, due to high "squitter" rates and 70% to 80% reply efficiency, the time for acquisition can range from .25 sec to 1.0 sec depending on range. Acquisition of the Butler 1066 beacon, with a lower "squitter" rate (1000 PPPS) and no station identification pulses is somewhat shorter. The shortest potential acquisition time is that for the Vega Beacon (0.07 sec) since the Vega broadcasts no "squitter" and no identification pulses.

The station dwell time of 1.0 second used by the RAPPS system was more closely tied to internal requirements than station acquisition time. The Tektronix 4051 intelligent terminal needed 4 to 5 seconds to compute its real-time graphic representation of aircraft progress, and so a dwell time of 1.0 second per channel for the 6 channels gave the Tektronix 4051 the time it needed for its computational cycle.

3.1.3 Power, Sensitivity and Path Loss

The KDM-7000 airborne interrogator power is constant at 1000 watts. The minimum detectable signal (MDS), considering a receiver band width of 1.2 MHZ and noise associated losses, is -103dBM. The KDM-7000 triggering level is -93 dBM, about 10 dB above the MDS.

This 10 dB figure is also typical of the VORTAC and Butler beacons. The Vega beacon, since it need not broadcast "squitter" formed from received noise, is less sensitive, exhibiting an MDS of -89dB. The norminal triggering level is 16dB above that figure.

Air to ground, the KDM-7000 maximum range to a VORTAC or to Butler 1066 and 1020 beacons is 400 statute miles. Range to a Vega beacon is, however, 40 statute miles because the Vega receiver is less sensitive. Beyond 40 statute miles at the above frequency and attenuation, the Vega would not "hear" the interrogator.

Ground to air, a VORTAC with a 4 KW power output has a maximum range to a KDM-7000 airborne interrogator of 800 statute miles. A Butler 1020 at 1 KW has a 400 statute mile reply range. A Butler 1066 with a power output of 100 watts has a 128 statute mile reply range. A Vega with 400 watts power has a 200 statute mile maximum reply range, but maximum operating range is limited to the 40 mile interrogation range limit.

3.2 THE DATA COLLECTOR AND REAL-TIME DISPLAY

The data collection microcomputer used as the heart of the data collector is an Intel Model 80/20-4. It interfaces with the DME ranging interrogator (KDM 7000) through the use of a wire-wrap circuit board mounted in the microcomputer chassis. This board controls the selection and sequencing of TACAN channels tuned through use of the panel of six thumbwheel frequency selectors. It accepts data regarding range measured from the DME interrogator and feeds the data, along with the channel identifier, to the microcomputer bus. The board also drives six LED indicators which indicate in real time the channel selected and the DME mode (acquisition versus tracking).

A standard RS-232C serial telecommunications interface is provided for each of the following: Tektronix 4051 graphic terminal, Tektronix

4923 data cartridge recorder and Tandberg SCDR-3000 data cartridge recorder. Serial interfaces are also provided to decode the Teledyne TDL-424 CDU data stream, the Teledyne TDL-711 CDU data stream and RDU data stream. The time/date clock is interfaced through a parallel port arrangement, as is the blind encoding altimeter (Narco Model AR-500). Aircraft power available for the test is 14VDC. Primary 60 Hz 115 VAC power for most of the equipment was provided by a 500 VA sine wave inverter. The DME interrogator required 115 VAC 400 Hz power which was provided by a 400 Hz sine wave inverter driven by a 12/24 V DC-to-DC converter. The data acquisition rack is pictured in Figure 3.1. The relevant major components are identified in that figure.

The real time display, consisting of the Tektronix 4051 terminal and BASIC language software package, was set up to provide a real-time plot of RAPPS DME derived position and Loran-C derived position. This capability was not needed for purposes of the Loran-C West Coast Test program, and so this capability was not evaluated.

3.3 PHYSICAL CHARACTERISTICS OF RAPPS

The RAPPS package was mounted in a standard 19" open rack enclosure, with the Tektronix 4051 terminal mounted on top (the terminal was detachable to allow entry and egress to the aircraft). The rack itself stands approximately 30" high, while the 4051 adds about 15" to the overall height. Weight of the RAPPS package is 196 lb, with the 4051 adding 55 lb to that total. The package draws approximately 910 watts at 14 VDC, according to the following budget:

Tektronix 4051	13A	
Intel System 80	13A	
Clock	3A	
Tandberg Recorder	6.4A	
Tektronix Recorder	4A	
DC/DC inverter & load	13.6A	
60 Hz inverter quiescent load	12A	
TOTAL	65A	@14V = 910W

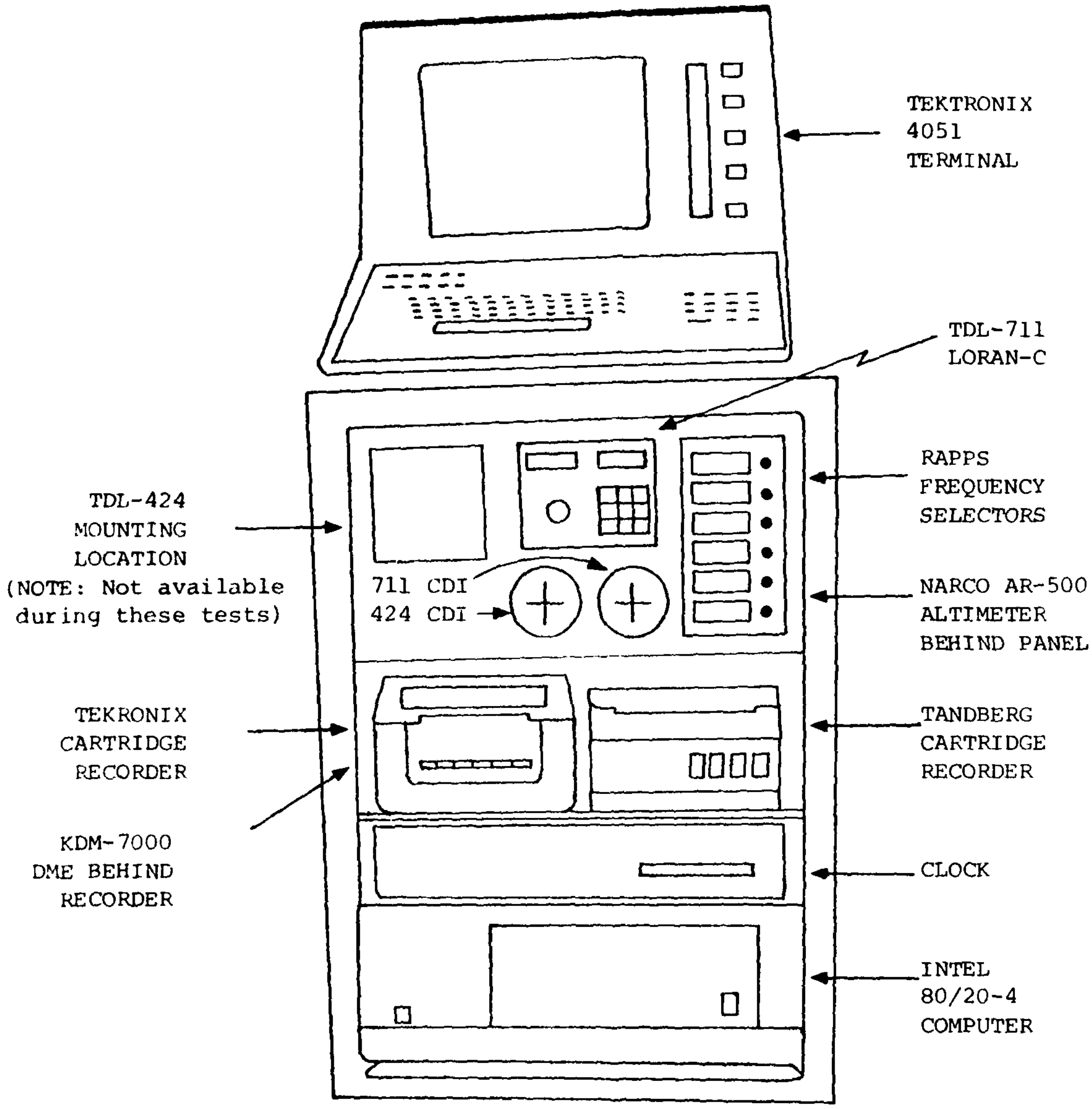


Figure 3.1 RAPPS Data Acquisition Rack Configuration

4.0 PERFORMANCE OF THE RANGING SYSTEM

4.1 RANGING SYSTEM IMPLEMENTATION PROBLEMS

There are several systematic problems which can arise in any implementation of a multilateration system:

1) Geometric dilution of precision (GDOP)
2) Limited availability of beacon transponders
3) Inability to acquire a valid range measurement due to range or line of sight restrictions, aircraft/antenna null points or multipath propagation.
4) Large, random ranging errors due to multipath propagation or other problems
5) Residual noise-induced ranging error
6) Beacon bias error
7) Beacon survey accuracy

Geometric dilution of precision (item 1) occurs with a moving test vehicle since, as the vehicle moves through the instrumented range, the crossing angles of the lines of position (range circles) from any two beacons may vary from very acute angles through a right angle (optimum) up to very obtuse angles. The measurement errors will be amplified in proportion to the inverse of the sine of the crossing angle. This is particularly important where only two ground beacons are being used to cover a given approach path. Thus, good positioning data is received only in a confined region of the entire coverage area. The usual means of combatting this problem is first, careful planning of beacon locations, and, second, provision of more than two beacons to cover a given flight path. For purposes of this test program, a generic beacon configuration shown in Figure 4.1 was used as the model for siting beacons at each of the five test sites. This configuration accurately covers the ten-mile length of the approach course while minimizing the number of beacons required. Item 2, the limitation on available beacons, stems primarily from the difficulty of siting and manning the beacons themselves, not from a simple lack of beacon hardware. Also, wherever possible, existing VORTAC stations were used to avoid siting unnecessary beacons.

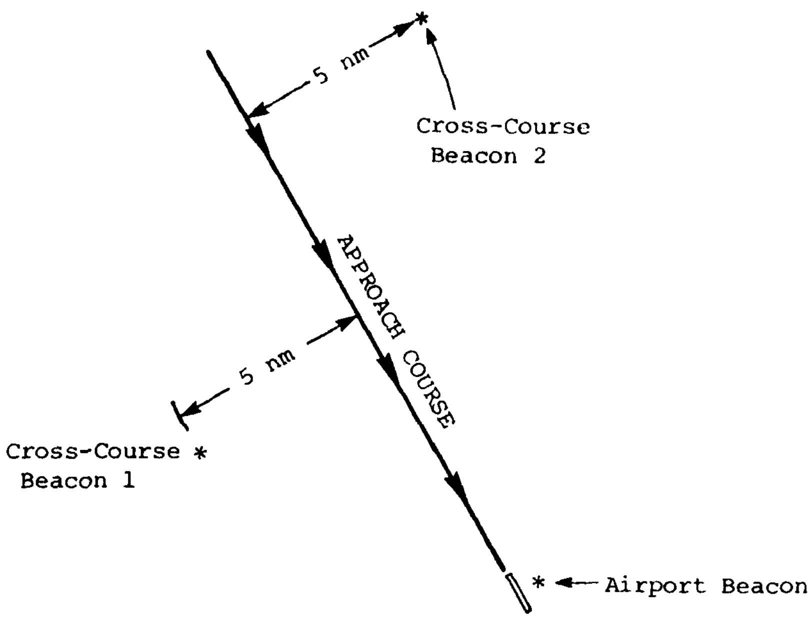


Figure 4.1 Model Beacon Geometry

One of the most pressing problems associated with a DME ranging system is the inability (due to several causes) to acquire a valid range measurement from a beacon at any desired time. A primary cause is simply the maximum downlink/uplink range at which a measurement may be successfully made, given the transmitter powers and receiver sensitivities available. Another cause is terrain masking of the line-of-sight signal. This factor precluded usage of beacons located further than 15 to 20 miles from the airport during most of the flights conducted during this test program. Two other causes of range acquisition problems, which are intermittent in nature, caused considerable difficulty during this test program. Range and line-of-sight limitations can be planned for prior to conducting a test. This led to a philosophy of ensuring that three beacons would be available within ten miles of each airport to be utilized for test in order to assure continuous, redundant coverage and good geometry. However, the intermittent nature of signal dropouts due to aircraft antenna pattern null points (sometimes called "antenna masking") and due to signal cancellation resulting from multipath propagation, led to very significant

problems in the post-flight calculation of position information. The antenna null problem was foreseen, but not judged to be of importance since the aircraft was expected to be stabilized on the approach course during the critical data collection periods. This proved to be somewhat optimistic since it rendered analysis of the initial approach transition, final approach and missed approach segments difficult. The magnitude of the multipath signal cancellation problem was essentially unexpected. This problem occurred primarily at South Lake Tahoe airport, and affected interrogations of the beacon located at the airport. The cause of the signal reflection was apparently the lake itself, which was rather calm and smooth during these tests. The phenomenon was manifested as a low probability of acquisition of the primary (line-of-sight) signal path, and a relatively high probability of lock-on to a false range indication due to multipath from other sources. These sources are plentiful at Lake Tahoe, which is ringed by steep mountains. The net result was that the airport beacon was rendered worse than useless. This was further compounded by the unfortunate fact that, contrary to original plan, the coverage geometry from the other two primary beacons available during part of the test was poor in the immediate vicinity of the airport (this beacon placement problem is discussed further in Section 4.4). The multipath problem is considered in detail later in this section.

The fourth item in the list at the front of this section concerns the effects of either interrogator problems, RAPPS data acquisition problems or multipath interference as they create occasional large, seemingly random ranging errors. These erroneous measurements generally occur in three forms: measurements somewhat larger than the true range, measurements of near-zero range, and a measurement of 111.11 miles on channel 1. The first problem is probably the result of multipath propagation. The second problem seems to be either a characteristic of the DME interrogator used with the RAPPS package, or some problem with the interface hardware whereby a false or non-existent range measurement is erroneously flagged as being valid. The third problem is a characteristic of the data acquisition package whereby (for some unknown reason) the data buffer reserved for DME data does not become completely filled with new data during a scan. Since the system initializes all buffer

positions to the character "1", the seemingly valid 111.11 mile measurement can appear.

The fifth item listed refers to the residual range measurement error which is characteristic of DME systems. It is the result of noise, pulse shape errors, range attenuation, nonlinearities, beacon jitter, etc. It is generally far smaller than any of the other error sources or types identified. The sixth item refers to the constant (slowly varying) bias which is characteristic of all beacon transponders. For purposes of this test, the portable beacons were preset in the laboratory to yield a net bias of zero when interrogated by the DME used with the RAPPS system. Thus the biases of these beacons may be assumed to be zero. When operational VORTAC stations are involved, however, the biases are unknown. Where possible, such stations were interrogated from a known location in order to ascertain the magnitude of the bias. This could not be done for most of the VORTACs involved due to line-of-sight limitations. Also, in at least one case, it was not possible to accurately determine the exact position of the aircraft when the reference interrogations were made. In another case, over-the-horizon measurements to a beacon which was only a few miles away could be successfully made, but the readings so made fluctuated by several hundred feet in a short time span (probably due to multipath effects), thus negating the effort to determine the bias. The beacon involved and measurements made are listed in Table 4.1. VORTAC station biases which could not be measured directly were estimated through a trial and error process during the Loran-C data reduction process[1]. Bias values were selected which minimized DME multilateration residual errors over a flight path in the coverage region.

The last cause of potential DME measurement errors is the inaccuracy inherent in determining the locations of the beacons. There are several methods available for finding beacon locations. These include:

- Location of the beacon at or near a known survey benchmark
- Usage of a satellite-based electronic survey system
- Professional land survey

Table 4.1 Ground Static Calibration Data

AIRPORT	BEACON SITE	ACTUAL RANGE (NM)	RANGE MEASUREMENTS (NM)	MEASUREMENT ERRORS (NM)
Stead, Nev. (See Figure 2.4)	Stead Airport	0.3112	0.32, 0.32	.01, .01
	Peavine Mt.	5.2700	5.29, 5.29	.02, .02
	Desert Research Inst.	1.0434	1.03, 1.03	-.01, -.01
	Reno VOR	12.4388	12.53, 12.44	.09, .00
	Reno VOR	12.4388	12.54, 12.54	.10, .10
Klamath Falls, Oregon (See Fig.2.2)	Stukel Mt.	6.1879	6.24, 6.24, 6.25, 6.24	.05, .05, .06, .05
	Stukel Mt.	6.1879	6.24, 6.24, 6.25, 6.25	.05, .05, .06, .06
	Stukel Mt.	6.1879	6.25, 6.25, 6.24, 6.24	.06, .06, .05, .05
Inconsistent Readings	Spring Lake	3.9192	4.25, 4.08, 4.09, 4.14	.33, .16, .17, .22
	Spring Lake	3.9192	4.10, 3.88, 4.13, 4.12	.18, -.04, .21, .20
	Klamath VOR	1.0207	1.09, 1.09, 1.09, 1.09	.07, .07, .07, .07

- Usage of existing survey blueprints and estimation of beacon location by reference to known landmarks
- Usage of U.S. Geological Survey (U.S.G.S.) Quadrangle charts and estimation of beacon location by reference to known landmarks
- Usage of a local coordinate system

The last technique involves manually laying out beacons with measuring tape and surveyor's transit. It is useful where positioning data relative to lat/lon coordinates is not needed, and where the instrumented range is quite small. In the mountainous terrain characteristic of these tests this technique was unusable. The most reliable techniques are the first three. The first (location near a known survey monument) was used wherever possible. Data describing the exact coordinates of these monuments is readily available. There were not always such monuments available in the general area where beacon installations would be desirable; hence, other methods were used.

The second technique, usage of a satellite-based electronic survey system, would have been ideal for a test such as this. However, such equipment was not readily available and is quite costly to purchase. It has one disadvantage for tests such as these: the receiver must be left in place for one day or more in order to get an accurate fix. This would require sending a crew to a location in advance of the actual test. The great advantage is that an accurate fix may be obtained regardless of disadvantageous terrain or remoteness of location.

The third technique, a professional land survey, would also have required considerable advance work in order to set up to survey the beacon locations. In lieu of that, existing survey blueprints and U.S.G.S. Quadrangle charts were used extensively. The quadrangle charts, many of which are based on photogrammetry, were found in most instances to be far superior to available local survey data. A particularly illustrative case in point involved a survey blueprint of Reno Stead Airport obtained from local city records. That survey was quite old, apparently having been performed by the Air Force while Stead was an Air Force base. After puzzling over some inconsistent data taken based on

that survey, the survey was compared to the appropriate quadrangle chart and found to be in error by several tenths of a mile. Subsequent usage of quadrangle chart data produced consistent results at Stead.

Usage of quadrangle charts was not without problems. To be easily located accurately, beacons should be placed near permanent physical features, such as buildings, roads and streams. Since they are usually quite out of date, modern buildings often do not appear. Furthermore, some features are illustrated by symbols rather than exact representations. This created a significant post-flight data analysis problem at Klamath Falls, Ore. One of the beacons was located atop Stukel mountain. It was positioned a measured distance from one of a group of four antenna towers at that location. The towers appeared on the quadrangle chart. However, they are depicted symbolically and so are not accurately postioned on that chart. This problem was eventually resolved during the Loran-C data analysis phase by adjusting the estimated beacon position until all three beacon range measurements were in good agreement throughout an approach procedure. In retrospect, while the quadrangle charts are very useful for determining beacon locations, great care must be excercised when placing beacons in order to insure that associated landmarks appearing on the charts are properly identified.

4.2 MEASURING THE PERFORMANCE OF THE RAPPS RANGING SYSTEM

An analytical and graphical procedure for assessing the performance of the DME-based RAPPS ranging system has been developed. Two performance measures have been developed. The first, called "reply efficiency" is a direct measure of the frequency with which a given beacon is successfully acquired during a test flight. As will be illustrated below, the ability to successfully interrogate a beacon is strongly dependent on the line-of-site restriction. This problem comes up very frequently during the tests, particularly due to the uneven terrain and the fact that the aircraft descends to within a few hundred feet above ground level. The second performance measure is called "error frequency". This is a measure of the frequency with which the individual range measurements are in error by a significant extent. Note that such errors may stem from the

operation of the interrogator aboard the aircraft (and all attendant signal propagation problems) or from the operation of the data acquisition system and interfaces to the interrogator.

The measurement of reply efficiency is quite straightforward since it only involves an examination of the data in order to count replies received for a given beacon per unit time. Such results are best illustrated graphically, as shown in Figure 4.2. The top half of this figure shows reply efficiency over a thirty minute period during approach testing at Klamath Falls. See the beacon layout in Figure 2.2 for reference. In the example of Figure 4.2 the three beacons are designated LMT (Klamath VORTAC, elevation 4090 feet), SPL (a beacon located near Spring Lake, elevation 4100 feet) and STM (a beacon located on Stukel mountain, elevation 6400 feet). The beacon designators are on the left side of the figure. The upper part of the figure presents the reply efficiency data in the form of a time line for each beacon. Each time corresponding to the receipt of a reply to that beacon is represented by a vertical "tic mark" drawn at that time. If two of the six channels available for tuning are tuned to the same beacon, and two replies are received during the six-second scan period, a vertical line twice as high is drawn. Thus, for example, the line corresponding to STM shows a consistent series of double replies with periodic interruptions throughout the thirty-minute flight period shown. This results since the beacon is located 2300 feet above the airport and is in line-of-sight of the aircraft at all times. The interruptions occur while the aircraft is turning in preparation to initiate an approach. In some cases the bank angle of the aircraft results in an antenna null. In contrast, the SPL beacon, which is located only 3.25 miles south-southwest, suffers from line-of-sight limitations just due to rolling terrain and the fact that it is at the same elevation as the airport. This fact is illustrated graphically by the losses in reply efficiency illustrated in Figure 4.2, which occur periodically as the aircraft nears the airport on a descending course. Reception of the VORTAC on the field (LMT) is consistent since it is essentially within line-of-sight of the aircraft at all times.

The measurement of error frequency is extremely difficult under the conditions which previal in this case. Since an intended purpose of the West Coast Loran-C flight test was to demonstrate an operational test of

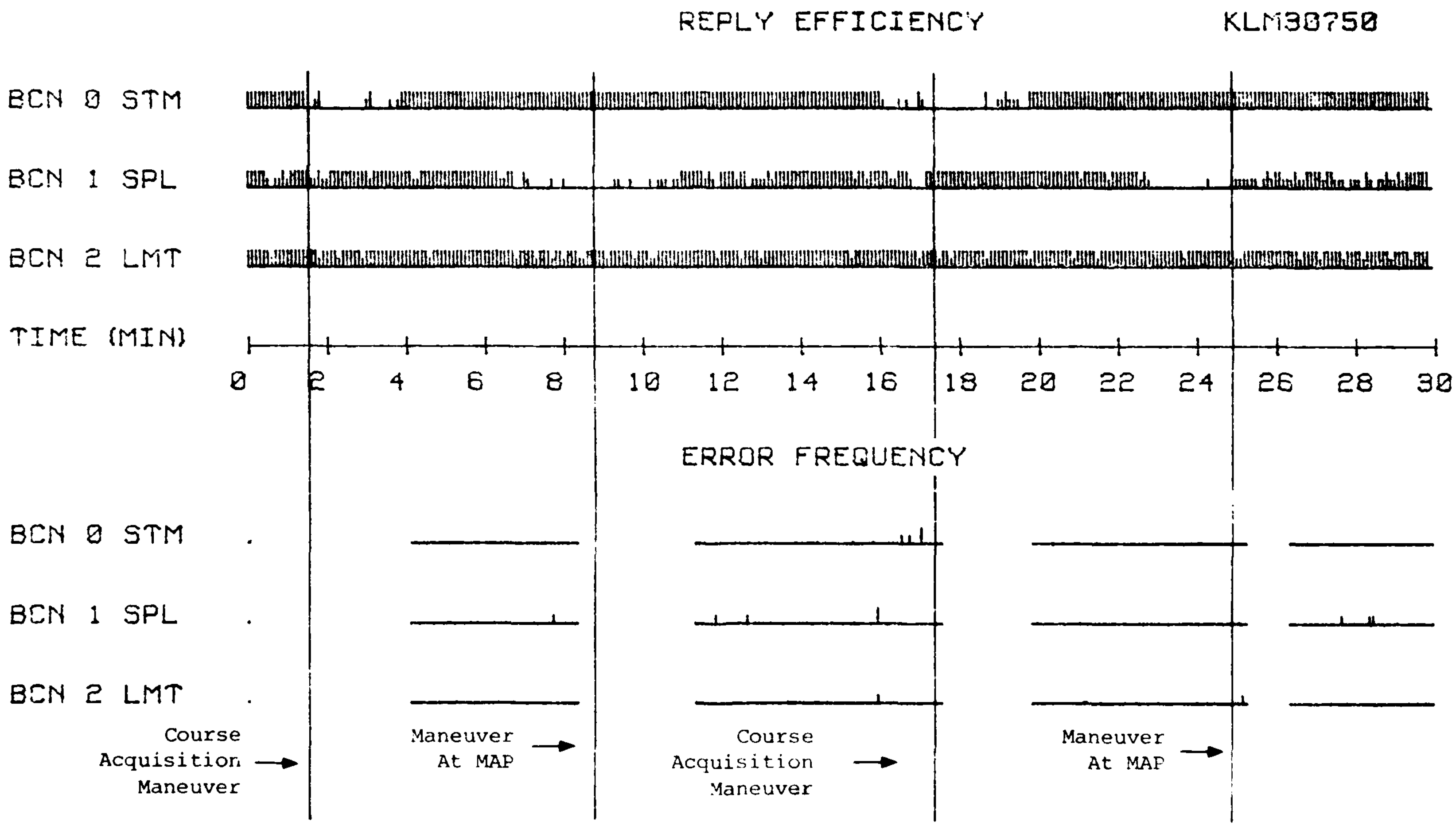


Figure 4.2 Beacon Performance At Klamath Falls (Plate A)

a subject navigation receiver utilizing the RAPPS system as the ground truth reference data source, there was no independent precision tracking range data available. While the RAPPS data was very useful for evaluating the performance of the Loran-C navigator, there is in this case no independent data source available for definitively evaluating the performance of the RAPPS tracking data. This fact was, of course, understood from the outset of this RAPPS evaluation study. The intended approach was to utilize whatever data was available from the test to obtain the best practical assessment of the performance of the ranging system. The approach taken here was to take advantage of the expected consistency in the Loran-C data. (Even though bias errors of a significant magnitude exist, they are expected to be relatively constant within the small region in which a given test flight is conducted.)

Because the DME data is known to contain occasional, randomly-occurring large errors, it was felt that the smoother Loran-C data could be used to advantage in isolating the deviant range measurements. In the course of the earlier Loran-C data reduction task a digital tracker scheme was developed which was utilized to identify range measurements which were grossly in error, and eliminate those from the minimum-squared-error multilateration scheme which was utilized to determine ground-truth position during the Loran-C error analysis. It was anticipated for purposes of this range measurement error analysis that a mixture of Loran-C and DME data could be used to obtain more consistent estimates of aircraft position over the entire flight. In regard to performing an overall assessment of significant DME errors, the original tracker scheme had two deficiencies: First, since gains were set high in order to accurately track the data during the stabilized part of the approach, the tracker would go unstable during any significant turning maneuver. Secondly, an improvement in the ability to resolve smaller range measurement errors was sought. There was also another problem, which occurred at only one location (South Lake Tahoe). The beacon geometry was such that the range-range solution becomes ambiguous as the aircraft arrived over the airport. The DME data tracker would often converge on the ambiguous (false) range-range solution and so would provide completely erroneous position information after that point.

By adding Loran-C data to the tracker algorithm, it was anticipated that these problems could be overcome.

The first step involved in developing a Loran-C tracking algorithm was to design an appropriate model to convert the time difference (TD) data which is available in the data stream to local X-Y coordinates centered in the region of interest. This model must be accurate so as to avoid any significant warpage of the Loran-derived position, but must also be computationally efficient. A highly accurate computational model was developed as a part of the previous study which met all U.S. Coast Guard Loran-C coordinate conversion requirements, including use of a spheroidal earth model. However, this model operates much too slowly for the present purposes. In its place a scheme was developed which utilized a procedure to calculate the gradients which relate X and Y coordinates to the two time difference coordinates. These gradients were calculated at the center point of the subject X-Y coordinate system. They can be used to accurately determine X-Y position relative to that center point for small perturbations in measured time differences. In order to accurately extend the linear conversion of TD's to X-Y coordinates to an area ±15 nm from the center point, gradient sensitivities to changes in time difference were also computed. From these factors (four gradients, eight sensitivities), X-Y position may be computed as a second order function of time difference.

$$\text{Gradient Matrix } G = \begin{vmatrix} \dfrac{\partial E}{\partial TD_{AB}} & \dfrac{\partial E}{\partial TD_{CB}} \\ \\ \dfrac{\partial N}{\partial TD_{AB}} & \dfrac{\partial N}{\partial TD_{CB}} \end{vmatrix} \qquad \text{I}$$

$$\text{Sensitivity Matrix } S_{AB} = \frac{\partial G}{\partial TD_{AB}} \qquad \text{II}$$

$$S_{CB} = \frac{\partial G}{\partial TD_{CB}}$$

where E,N are X,Y coordinates in the East and North directions, TD_{AB} and TD_{CB} are time differences for the master B and station A and C, respectively.

Positions may be found as follows, where ΔTD represents the difference in a TD measurement from the X-Y coordinate center point:

$$\begin{bmatrix} E \\ N \end{bmatrix} = \left(G + S_{AB} \cdot \Delta TD_{AB} + S_{CB} \cdot \Delta TD_{CB} \right) \begin{bmatrix} \Delta TD_{AB} \\ \Delta TD_{CB} \end{bmatrix} \qquad \text{III}$$

The sensitivity matrices were derived computationally, not analytically.

Given the above TD to X-Y coordinate conversion technique, a tracking filter was devised which would utilize the X-Y result as its input. The tracker so developed is a second order, α-β tracker which considered the following factors in the determination of position (α) and velocity (β) gains:

1) Expected magnitude of Loran-C random error component (standard deviation)
2) Expected standard deviation of aircraft longitudinal acceleration
3) Expected standard deviation of aircraft lateral acceleration
4) Update Interval

The detailed analysis and derivation of gains for the tracking filter are contained in Appendix A. The philosophy behind the α-β tracker was discussed in an earlier test report (Reference 1). The calculation of gains was complicated by uncertainty regarding the age of a given Loran-C data record. As discussed in that report and later in Section 5 of this report, there is a degree of randomness to the transmission of data by the Loran-C receiver to the data collector unit. At times the arrival of data streams is quite sporadic, while at others the stream is received regularly, once per second. Since the data collector was not designed to time-annotate each data item as it was received, the age of the Loran-C data record is not known accurately. There is, however, a certain amount of information available concerning the probable age of the data in the form of a count of the number of records received. As discussed in Section 5, this count ranges from zero to four transmissions received (even though up to six can actually be received during the data

collector time interval). This information was utilized as follows: if a count of four is received, the Loran-C data is treated as being current. If a count of zero is received, the Loran-C data is treated as missing; i.e., it is not used to update the tracker. If one, two or three Loran-C records are received, the data is utilized to update the tracker, but the gains are adjusted accordingly, as detailed in the Appendix.

The Loran-C tracker algorithm so constructed operates properly and tracks the data reasonably. However, when used to evaluate the consistency of the DME data, the inconsistency and unevenness of the Loran-C data becomes apparent. Also, when the aircraft executes even a mild turning maneuver or speed change, the tracker is slow to accommodate the change. Therefore, when used to evaluate the consistency of the DME data, the tracker output is sufficiently inaccurate that a large number of DME measurements can erroneously be judged to be inaccurate. Different tracker gains were tried but failed to yield any improvement. This fact lends verification to the assumptions upon which the original gains were based.

In order to further stabilize the tracker, it was decided to utilize the DME data itself as input to the tracker. This had to be done with care since some of the DME measurements contain significant errors and would totally mislead the tracker. Inclusion of the DME measurements is possible since part of the task of the tracker is to estimate Loran-C biases, which should remain relatively constant at a given location. In order to filter out grossly inaccurate DME readings, the DME error (the difference between the DME reading and a nominal range measurement calculated from the tracker position estimate) is compared in magnitude to a limiting value. If it exceeds that value, its contribution to the tracker input is limited to that value. The sums of these deviations expressed in northing and easting components over the six-second update period are used to update the tracker in addition to the Loran-C data. Two factors, the DME error gain and the DME error limit, were adjusted over wide ranges in a series of test runs in order to find the best values experimentally. A DME gain value of 75% of the Loran-C gain and an error limit of 0.1 nm were selected.

The RAPPS evaluation program produces two forms of output. The first, depicted in Figure 4.2, is a plot of beacon reply efficiency and error frequency versus time. Each plot shows thirty continuous minutes of flight data (due to plotter size and resolution limitations). Thus most of the test flights require three or four individual plots to depict the entire flight. The second output of the RAPPS evaluation program is a printout of beacon error statistics. A line is printed corresponding to each identified range measurement error. This is for purposes of manual analysis. For purposes of this analysis, the threshold used to differentiate a "large" error from a routine condition was set at 1000 feet. Thus a line is printed (and a line segment is plotted on the error frequency axis) for every DME measurement which deviates more than 1000 feet from the tracker-derived standard range. An additional printout is produced at the end of the run which prints out statistics for all those DME measurements which were within the 1000 feet limit. Mean and standard deviation for each beacon is calculated. Note that all DME measurements are corrected for slant range error effects before processing.

A final step in the processing is again related to the basic inability of a tracking algorithm to accurately track the data during turning maneuvers and speed changes. Also, there are periods when so much Loran-C data is missing that the data which does exist is difficult to track. In these cases, the program is unable to perform an accurate assessment of DME ranging errors. Therefore, a facility was introduced into the program which allows specification of analysis start and stop times for purposes of inclusion on the error frequency plots and in the range measurement statistics. The deleted time periods appear as breaks in the axis in the error frequency plots (see Figure 4.2).

4.3 RAPPS RANGING SYSTEM PERFORMANCE ASSESSMENT

For this section, the tools discussed in the previous section have been utilized in order to analyze the data taken at South Lake Tahoe, Klamath Falls, Grand Junction, Reno and Stead. The data taken at Stead was of somewhat limited value for purposes of evaluating the RAPPS ranging system. This was the result of a very tight flight pattern. The results were not analyzed since very little of the flight was actually flown in a steady state condition. Data taken at South Lake

Tahoe on July 7 (which was terminated due to an aircraft system failure) and on July 26 have both been analyzed. Some of the data taken at Grand Junction was near the triad baseline extension area, and so the data is quite noisy. This creates some difficulty in analyzing the data.

The beacon performance results for the tests at South Lake Tahoe on July 26, 1979 are presented in Figures 4.3 through 4.8. Two flights were flown, each providing approximately 75 minutes of data. In the first flight, four beacons were available (See Figure 2.2): RNO (Reno VOR), LTA (Lake Tahoe VOR), LTT (Lake Tahoe tower beacon) and MKB (Meeks Bay beacon). LTT and MKB were tuned twice. In the second flight, a fifth beacon (EMB, Emerald Bay beacon) was added.

A review of the six plots shows that RNO was picked up only occasionally. The replies, which were quite sparse, could be obtained only when the aircraft was at its northern-most (and highest) point, when intercepting the approach course. No ranging errors on RNO are shown. The Lake Tahoe VOR (LTA), being at a high elevation on a mountain, is picked up consistently throughout the entire flight. Dropouts were few and occurred with no apparent pattern. No errors were isolated during the first flight (See Table 4.2). The Lake Tahoe tower (LTT) beacon, which was tuned twice, was within clear line-of-sight view of the aircraft during the entire flight. However, range acquisition of LTT was very spotty even though it was in clear view. An examination of the plots reveals a periodic nature to the ability to successfully interrogate the beacon. Maximum success likelyhood peaks as the aircraft was flying east to intercept the approach course The probable cause of the LTT dropout is multipath off the lake. This is analyzed later in Section 4.4. Many ranging errors were also detected for LTT (seven gross data acquisition system errors and thirty-six multipath-induced errors). The high error rate is not difficult to explain given the apparently pervasive nature of the multipath; when the reflection off the lake cancels the direct signal, the possibility of some other signal, reflected off the nearby mountains, being acquired becomes significant. The Meeks Bay (MKB) beacon, being located higher above the lake, was received strongly throughout the flights.

Figure 4.3 South Lake Tahoe Beacon Performance (Plate A)

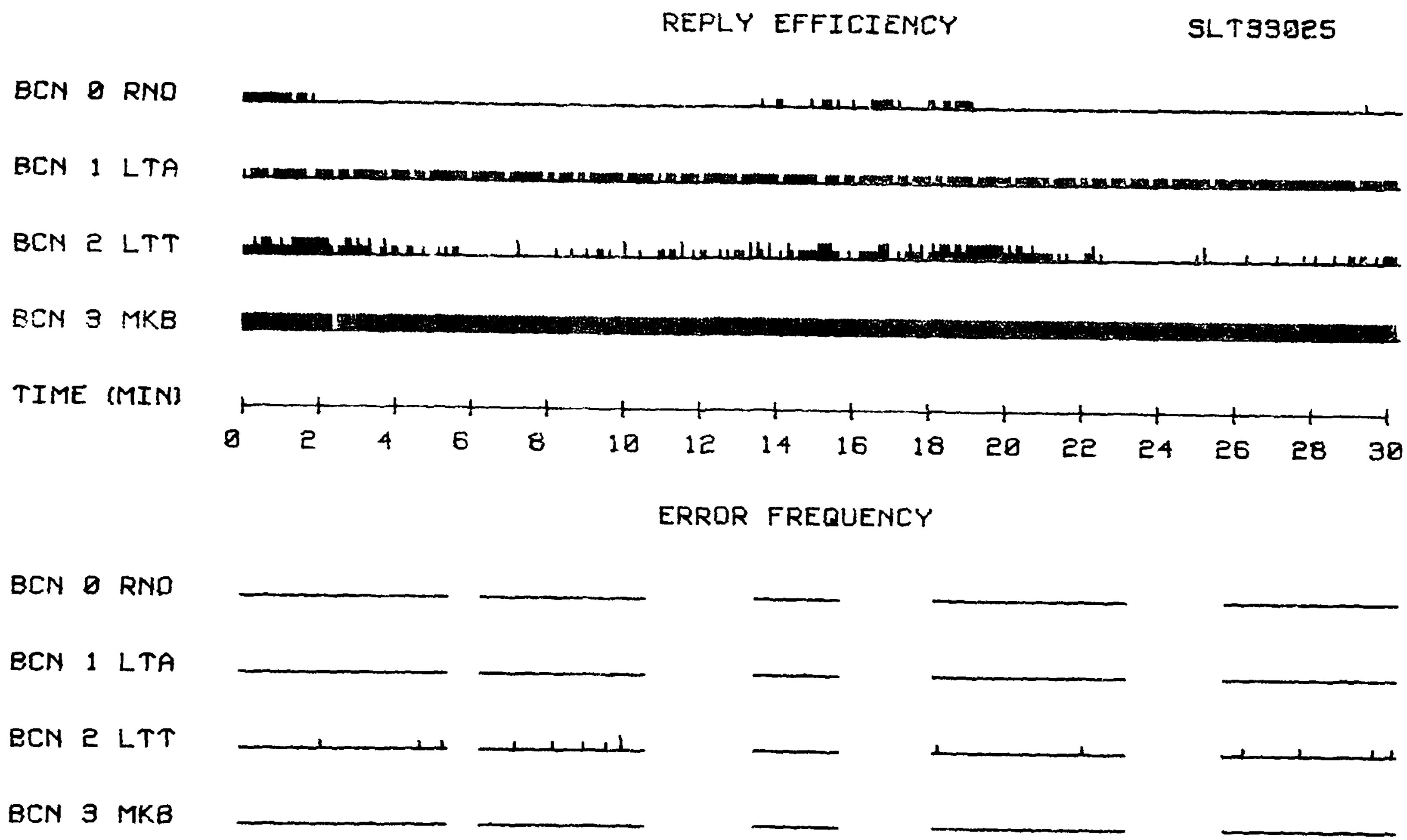


Figure 4.4 South Lake Tahoe Beacon Performance (Plate B)

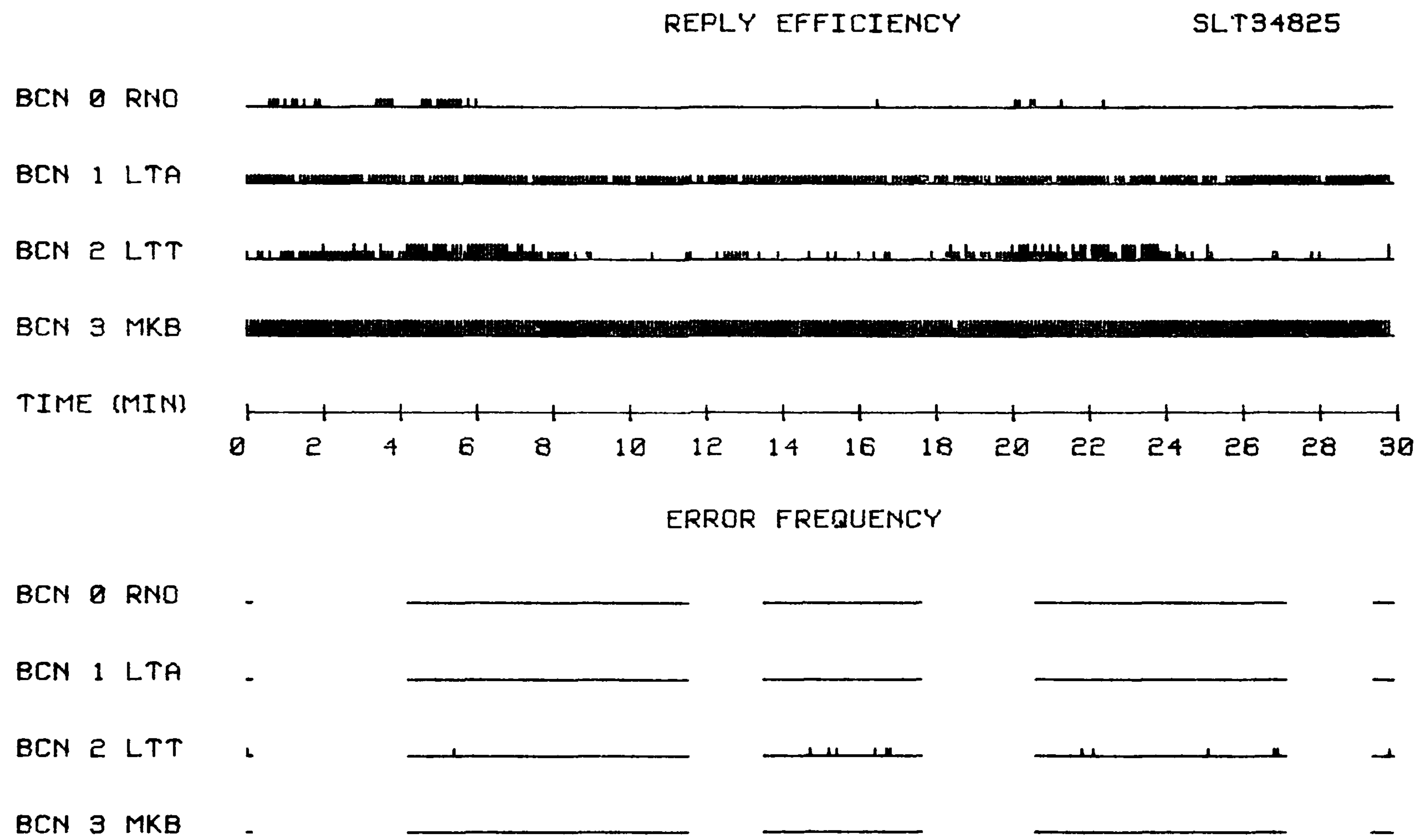


Figure 4.5 South Lake Tahoe Beacon Performance (Plate C)

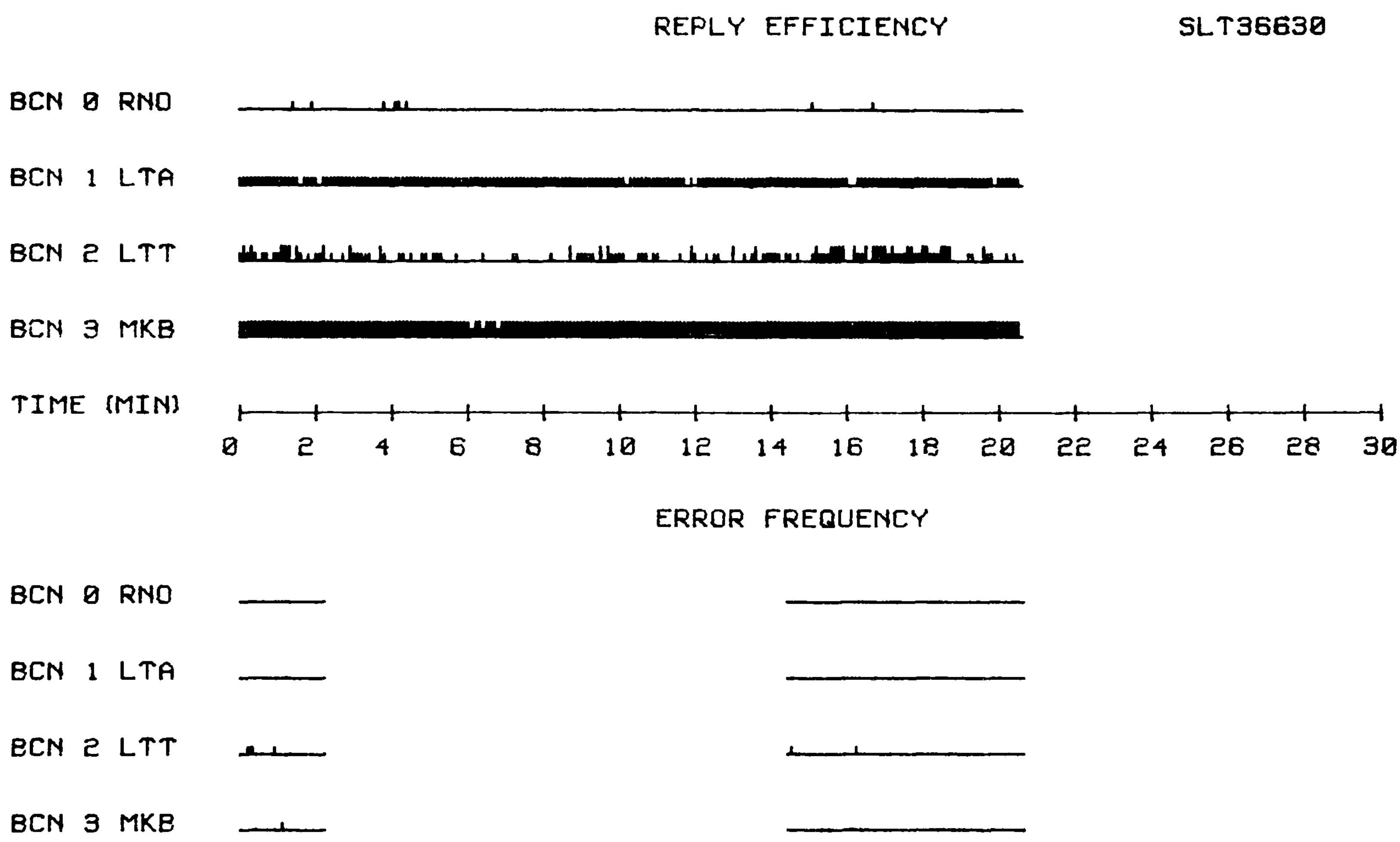


Figure 4.6 South Lake Tahoe Beacon Performance (Plate D)

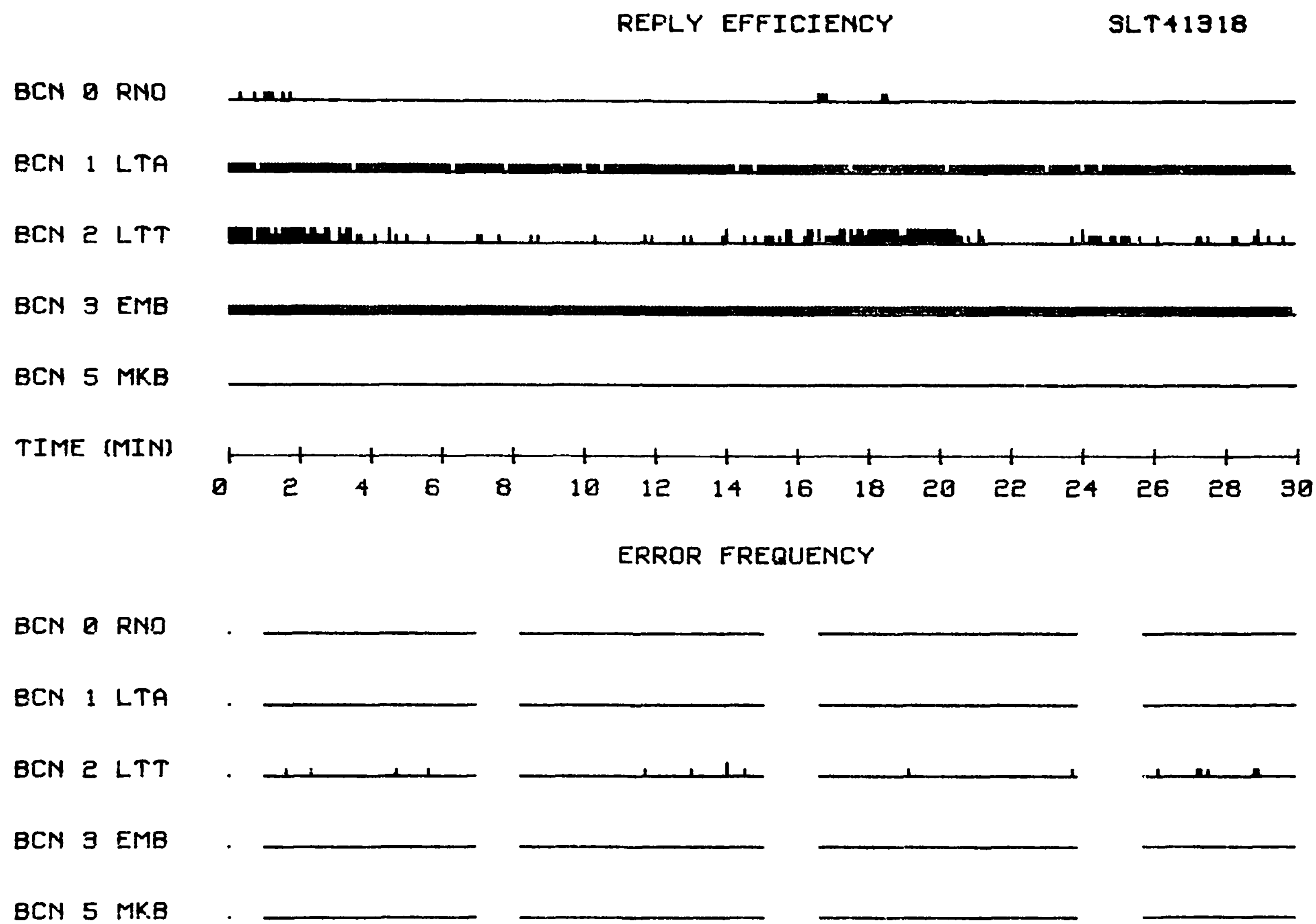


Figure 4.7 South Lake Tahoe Beacon Performance (Plate E)

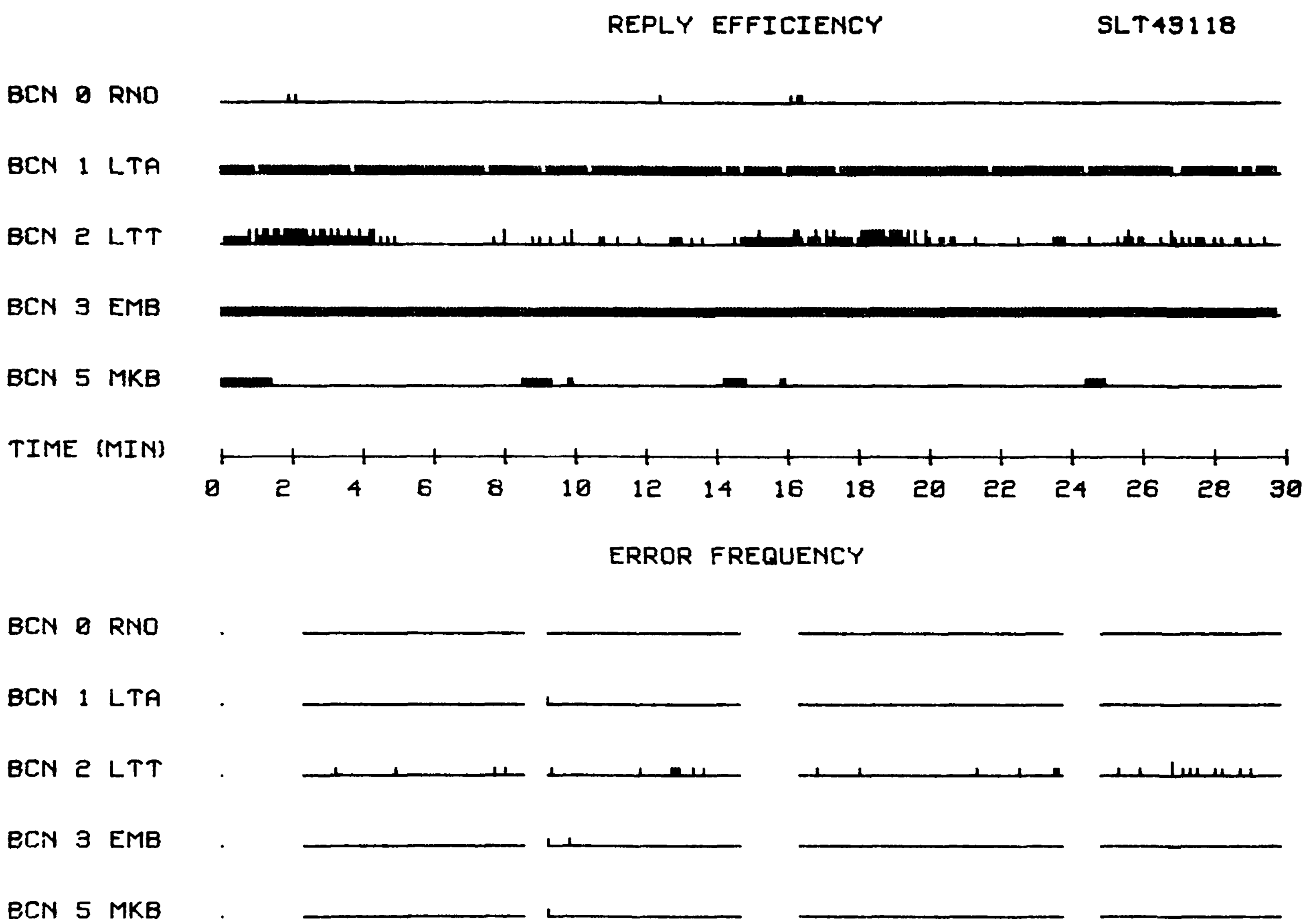


Figure 4.8 South Lake Tahoe Beacon Performance (Plate F)

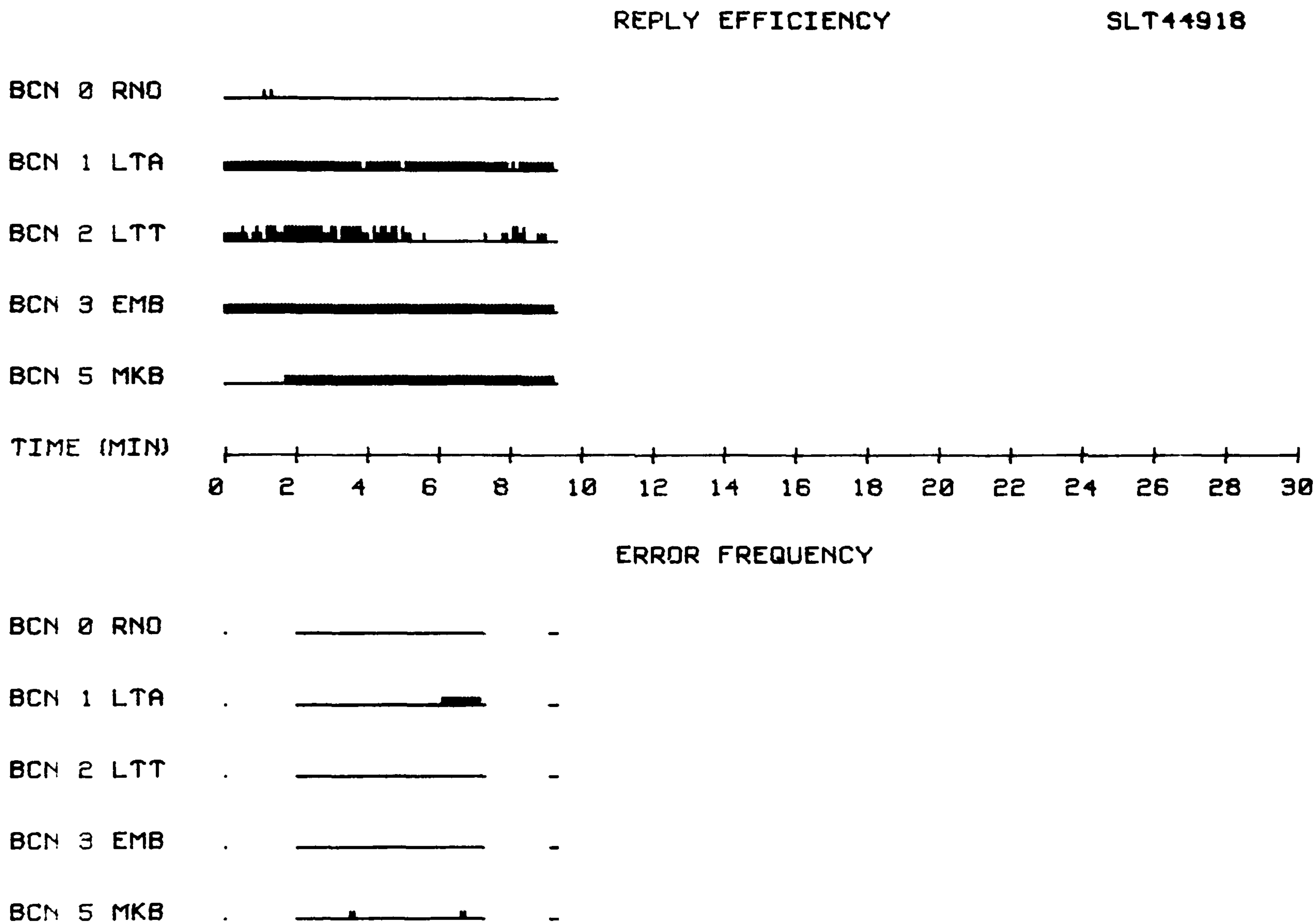


Table 4.2 South Lake Tahoe Beacon Performance Statistics (Flights on 7/26/79)

Beacon Code	Replies Analyzed	Gross Errors (Replies)	Multipath Errors (Replies)	Residual Errors	
				Mean	SD
RNO	62	0	0	67'	252'
LTA	844	0	12	162'	276'
LTT	659	11	56	35'	353'
MKB	790	0	6	-36'	233'
EMB	538	0	1	-63'	290'
Total	2893	11	75	35'	299'

The second flight of the day was conducted with the benefit of an additional beacon at Emerald Bay (EMB). That beacon was received consistently through the entire flight. The other beacon (MKB) had been turned off at the end of the first flight. Through a communications mishap, it was not turned on again until very late in the second flight. At the tail end of the flight (Figure 4.8), a series of errors are pointed out for LTA and MKB. These appear to be the result of the inability of the tracking algorithm to follow the data, rather than being range measurement errors.

The residual error statistics at South Lake Tahoe are quite reasonable, as shown in Table 4.2, 299 feet overall. The LTT statistic stands out as being higher than the rest, which is not surprising given the multipath problem which has been identified.

The beacon performance results for the tests at Klamath Falls on July 24, 1979 are presented in Figures 4.9 through 4.12. Two separate flights were flown. Approximately 43 minutes of data were taken on each. Three beacons were used (see Figure 2.3) and two channels were tuned to each beacon. Throughout the flight, consistent replies were received from the airport VOR (LMT). The reply efficiency line is virtually constant throughout, although a few ranging errors were detected. As is shown in Table 4.3, all six of these were of the multipath type, as

Figure 4.9 Klamath Falls Beacon Performance (Plate A)

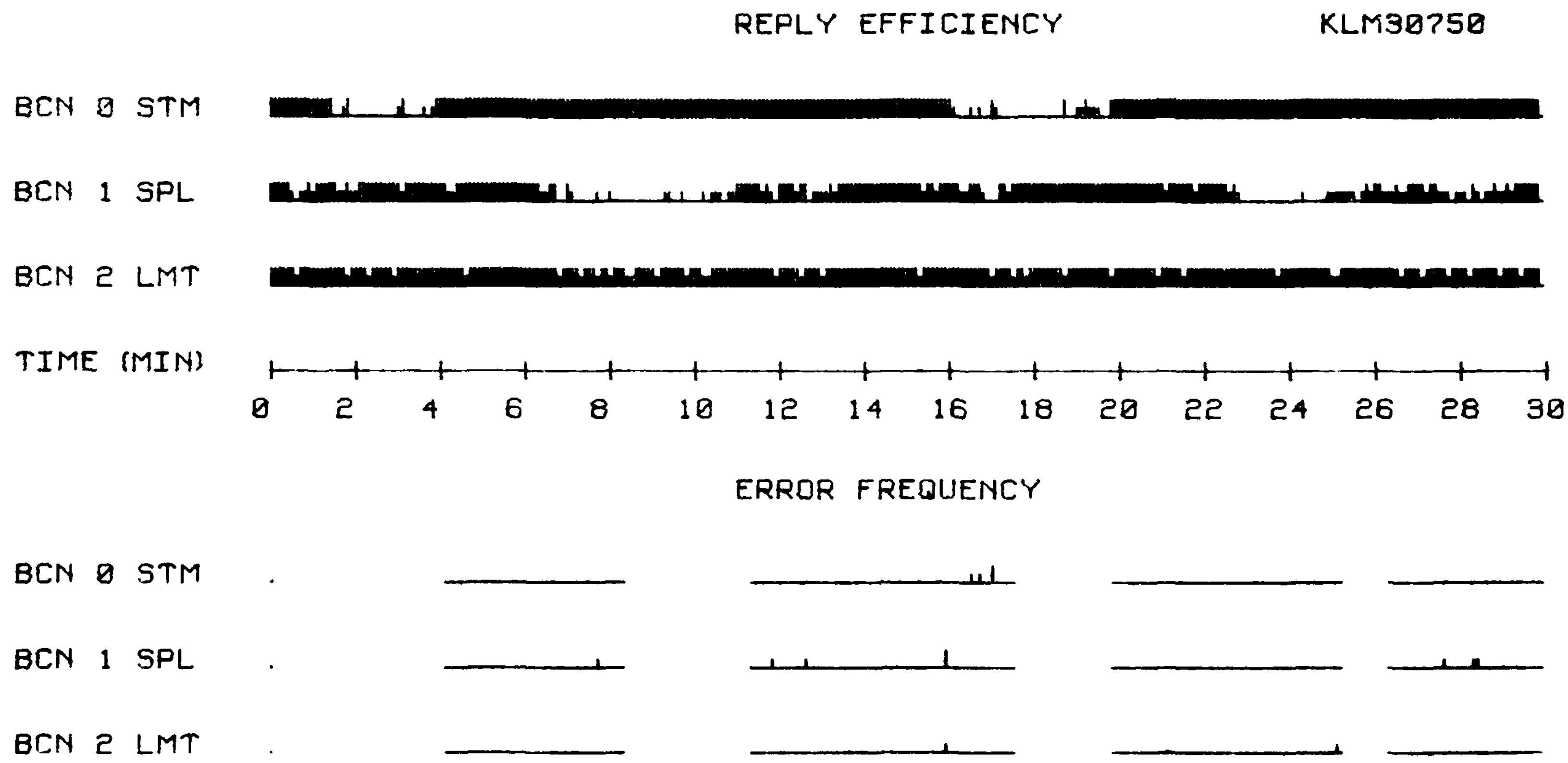


Figure 4.10 Klamath Falls Beacon Performance (Plate B)

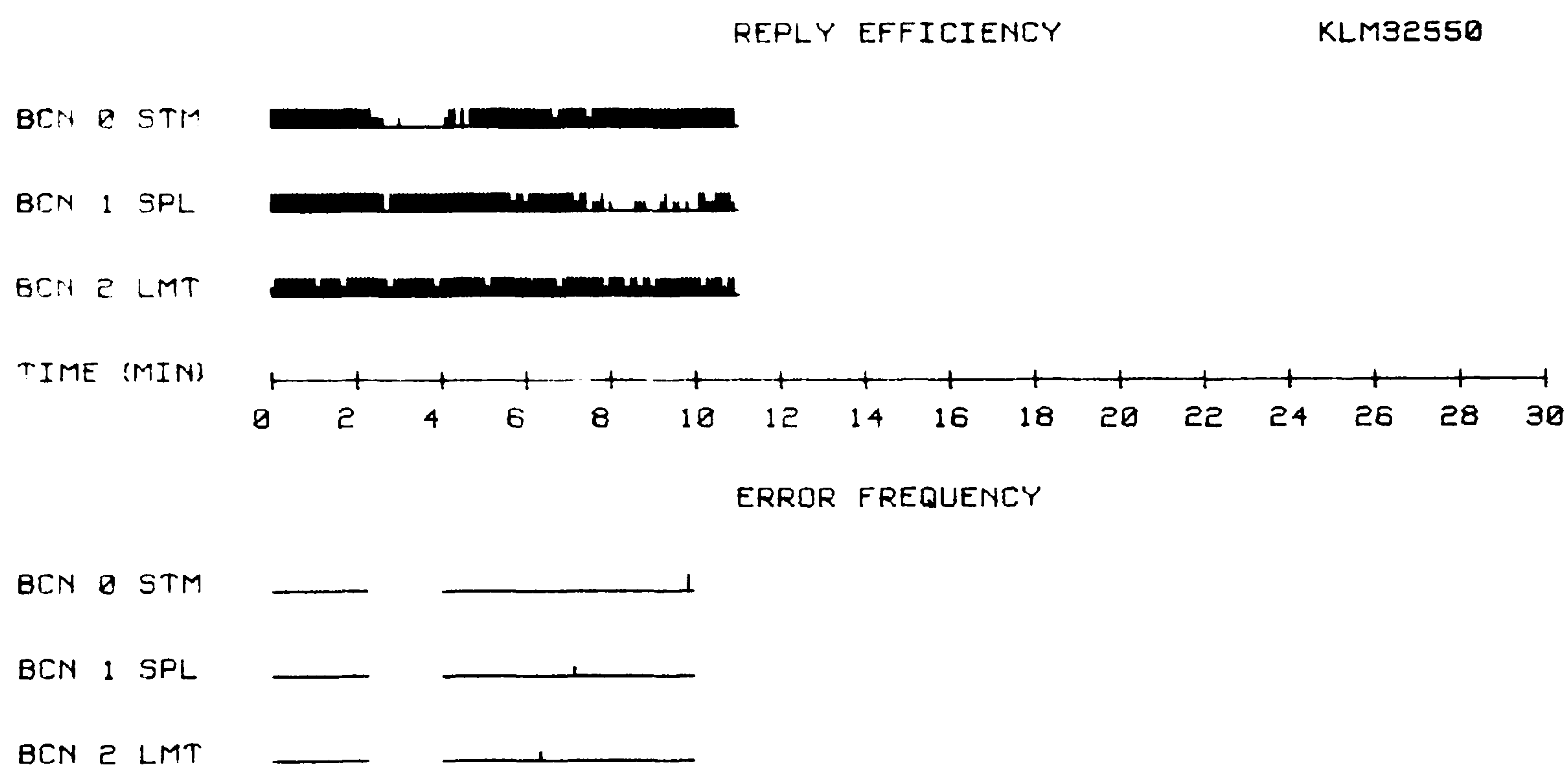


Figure 4.11 Klamath Falls Beacon Performance (Plate C)

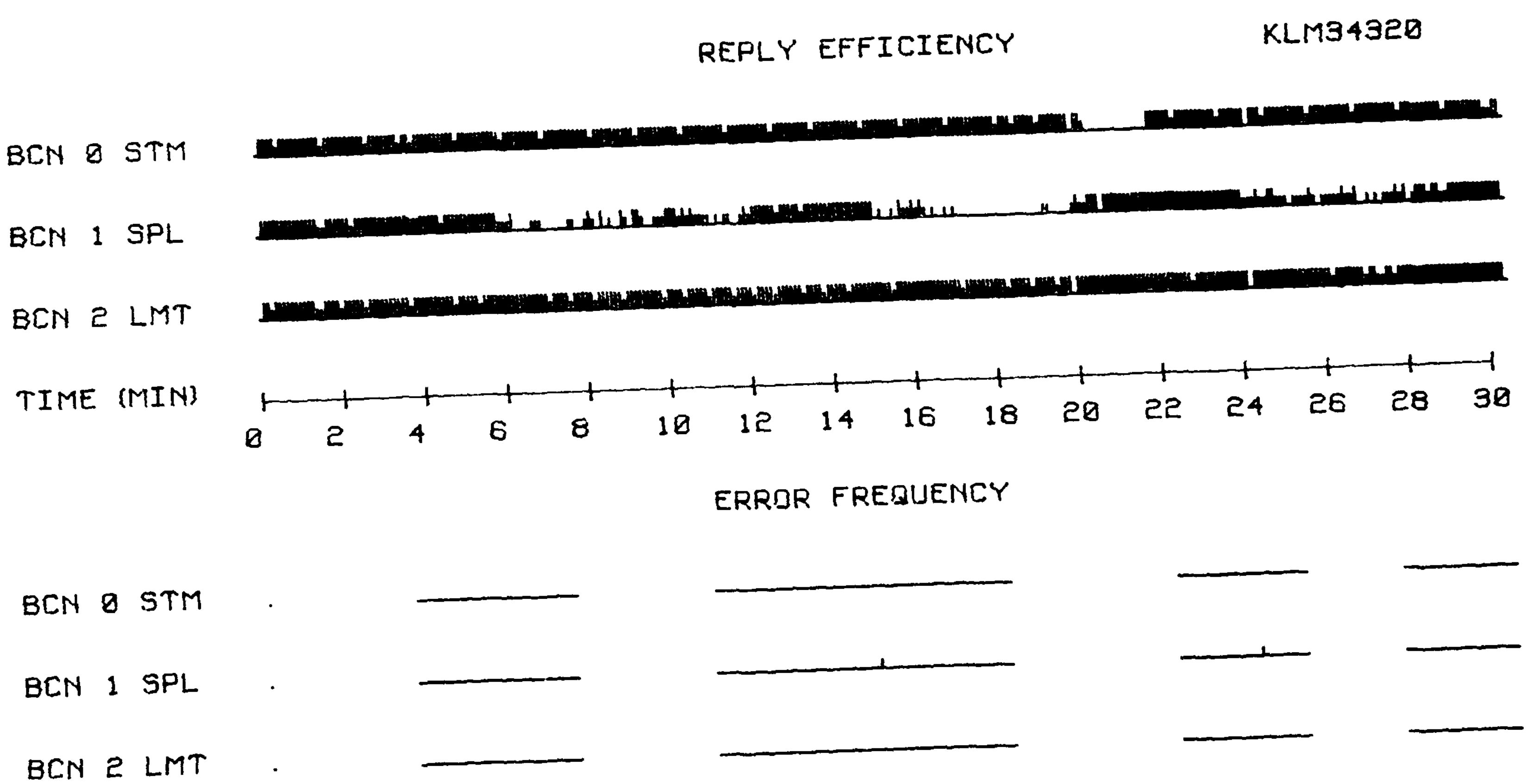
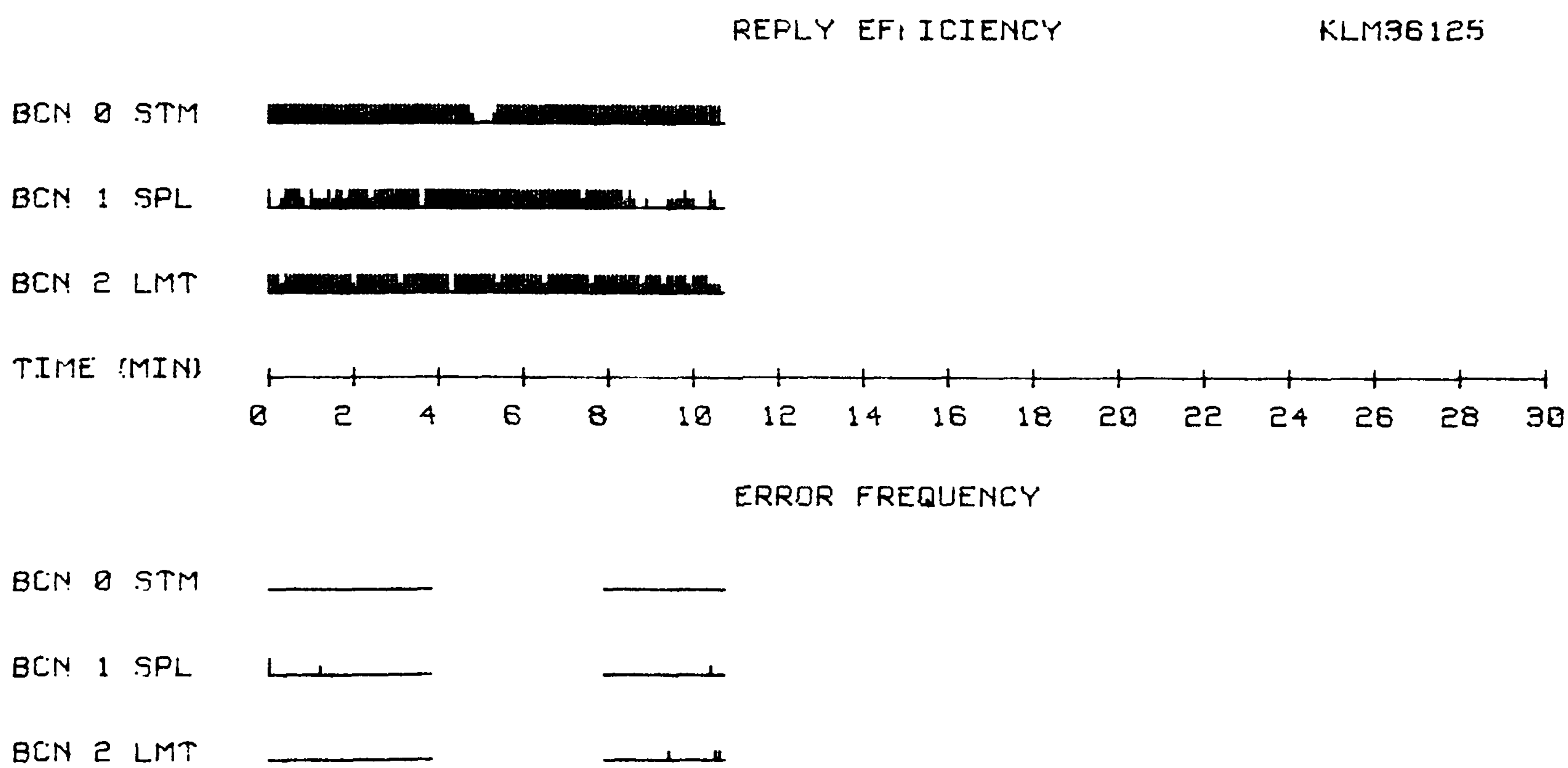


Figure 4.12 Klamath Falls Beacon Performance (Plate D)



opposed to being the gross, system-caused error indications. Data from the SPL beacon is strong during the approaches, but disappears as the aircraft drops in a altitude near the airport. Of the fifteen ranging errors detected, ten are of the multipath type. These seem to occur at points where ranging capability is marginal due to intervening terrain. Data from the Stukel mountain beacon is quite strong and consistent except where the aircraft turns to intercept the final approach course. Apparently this is the result of aircraft antenna shadowing. Of the six multipath-type errors which occurred, four occurred at one point where ranging capability is marginal.

Table 4.3 Klamath Falls Beacon Performance Statistics

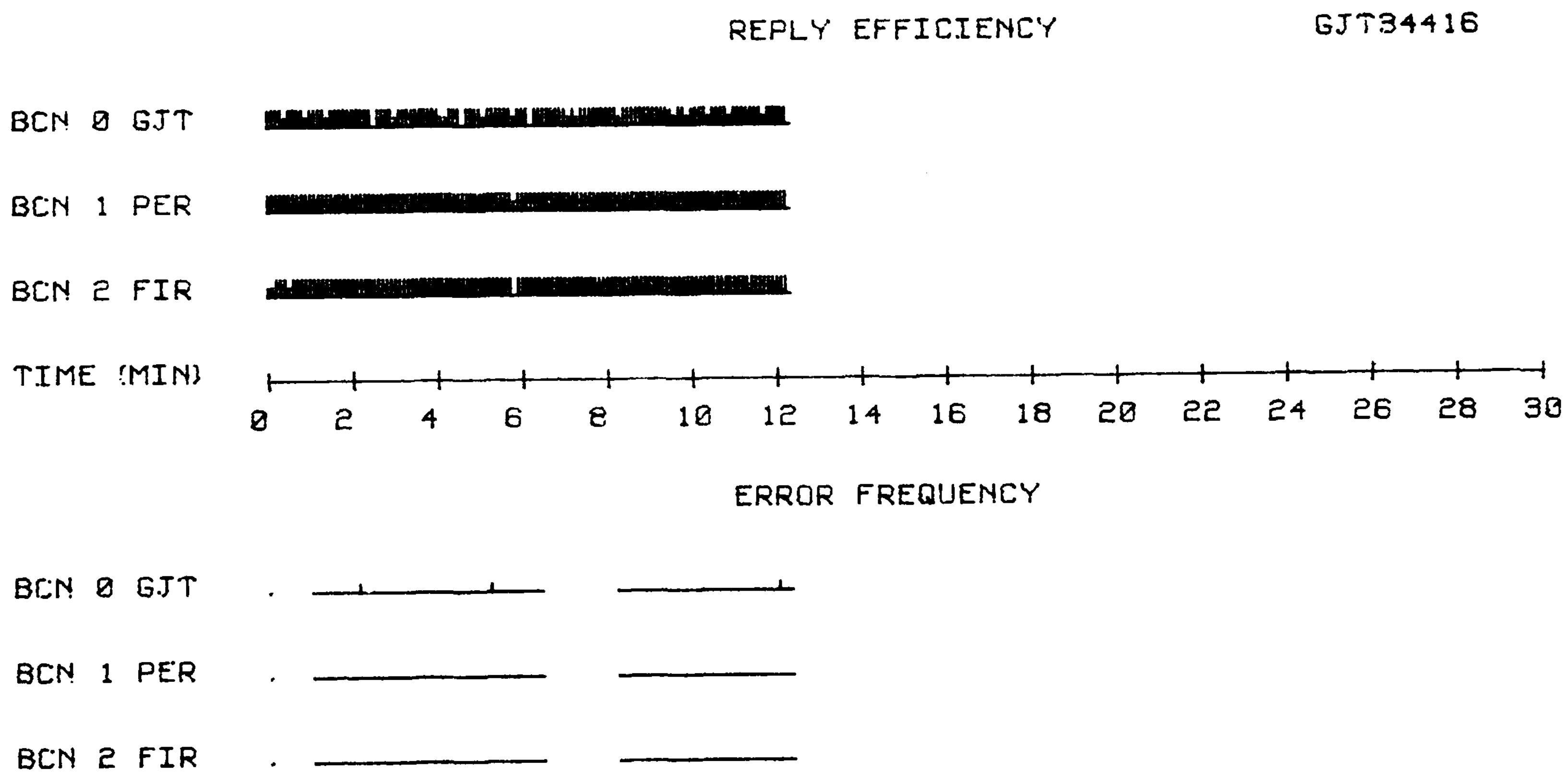
Beacon Code	Replies Analyzed	Gross Errors (Replies)	Multipath Errors (Replies)	Residual Errors	
				Mean	SD
STM	970	0	6	-48'	266'
SPL	710	5	10	-156'	278'
LMT	963	0	6	-101'	251'
Total	2643	5	22	-96'	268'

The residual error statistics at Klamath Falls are quite good (268'), and are even better than those measured at South Lake Tahoe.

The beacon performance results for the tests at Grand Junction on July 28, 1979 are presented in Figure 4.13. Only part of the data is presented, corresponding to data taken while flying relative to the Fallon-George-Searchlight (FGS) triad. Most of the flying at GJT was conducted using the Fallon-George-Middletown (FGM) triad (a baseline extension case). See Figure 2.5 for the locations of the stations and the Grand Junction airport. This resulted in very large biases (on the order of ten miles) which were removed by operating in the updated Loran-C mode. However, due to those large biases, it became evident that a beacon performance analysis could not be successfully performed.

During the FGS flying at Grand Junction, three beacons were used (see Figure 2.4) and two channels were tuned to each beacon. Consistent

Figure 4.13 Grand Junction Beacon Performance



replies were received throughout the flight from all three beacons. All were within line-of-sight at all times. Three multipath-type errors were detected, as shown in Table 4.4. All affected the GJT VOR, and cannot be correlated with any specific cause or circumstance.

Table 4.4 Grand Junction Beacon Performance Statistics

Beacon Code	Replies Analyzed	Gross Errors (Replies)	Multipath Errors (Replies)	Residual Errors	
				Mean	SD
GJT	172	0	3	87'	256'
PER	189	0	0	10'	193'
FIR	188	0	0	4'	159'
Total	549	0	3	32'	207'

The residual error statistics at Grand Junction are extremely good (207'), better than either of the other two locations. This result is, however, based on a comparatively small sample size.

The overall results of the residual error data derived at South Lake Tahoe, Grand Junction and Klamath Falls are presented in Table 4.5. In considering the meaning of the overall result, 285 feet, 1σ, it should be recognized that this value was arrived at without benefit of a precision, independent tracking system, and so serves as a conservative (high) estimate of the actual performance of the ranging system.

Table 4.5 Residual Ranging Error Summary

Location	Points	Mean	Standard Deviation
South Lake Tahoe	2807	35'	299'
Grand Junction	546	32'	207'
Klamath Falls	2616	-96'	267'
Total	5969	-23'	285'

4.4 BEACON PLACEMENT EFFECTS AND GUIDELINES

In the process of conducting this test program and processing and analyzing the results, much was learned regarding the layout of beacons for a successful test program. These factors fall into two basic groups: beacon planning, and actual layout of the beacons. In Section 4.1, several techniques for locating beacons were discussed. Specific problems along these lines will be discussed later.

A basic philosophy towards beacon placement was adopted during the planning phase of the West Coast Loran-C test program. This philosophy included the following tenets:

1) Utilize existing VORTACS whenever possible
2) Minimize the number of temporary beacon installations
3) Maximize the potential for accurately positioning the temporary beacons
4) Plan for ease of installation and power access

The basic approach was to position one beacon at or near the airport (Reno and Klamath Falls have existing commissioned DMEs on the airport already). This would provide coverage throughout the approach procedure. A second beacon was to be located to the side of the approach course (from 5 to 10 miles off course), approximately half way down the approach path (5 miles from the touchdown zone). At Reno and Grand Junction existing VORTACs fulfilled this role. The philosophy also included the use of a third beacon located in such a manner that some redundant coverage is provided, for the following purposes:

1) as a cross check for the other range measurements
2) as a substitute during times when a loss of signal (due to terrain masking, antenna null pattern or multipath effects) is experienced.
3) to improve overall positioning accuracy

As illustrated in Figure 2.1, the beacons utilized at South Lake Tahoe included a beacon on the airport (called LTT) and a beacon located to the side of the approach course (called MKB). In addition, two VORTACs were tuned: Lake Tahoe VOR (LTA) and Reno VOR (RNO). As was shown in Section 4.3, RNO, being behind mountains, was received only sporadically.

LTA was received almost continuously, being located at a high elevation accross the lake. Several unfortunate things related to beacon placement did occur, however. First of all, the airport beacon (LTT) was received only sporadically during most of the approach, and often was received in error. While it is impossible to indisputably determine the cause of this behavior, the probable cause is multipath reflections off of the smooth lake. Since the airport elevation is only slightly higher than the lake, the path length difference between direct and reflected signals is very slight, and changes very slowly as the aircraft progresses. This causes relatively long periods of signal cancellation. For example, in Figure 4.14 a hypothetical situation is illustrated showing a lake signal reflector.

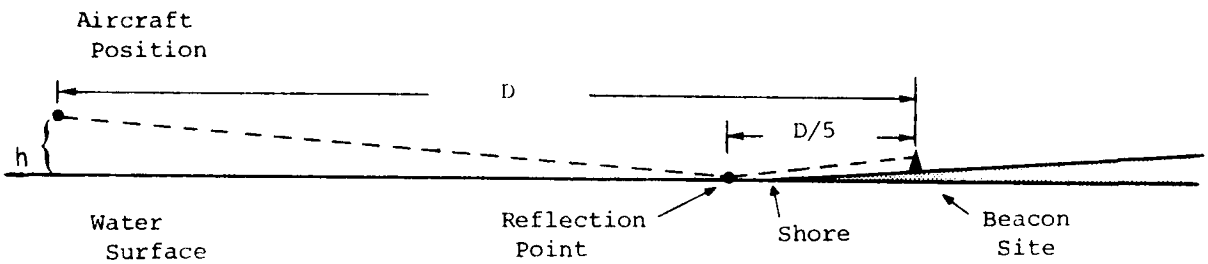


Figure 4.14 Hypothetical Lake Multipath Example

The direct signal path length is given by

$$d_D = \sqrt{D^2 + h^2}$$

The reflected path length is given by

$$d_R = \frac{D}{5} + \sqrt{\left(\frac{4D}{5}\right)^2 + h^2}$$

Using linear approximations to the square root function and combining terms, the range difference in this example is given by

$$\Delta d = \frac{h^2}{8d}$$

If $D = 10$ nm and $h = 3200$ feet, then $\Delta D = .0035$ nm, (21 feet). At $D \approx 8$ nm and $h \approx 2560$ feet, $\Delta D = .0028$ nm (17 feet). Thus in two miles the path difference changes by 4 feet. At 150 kt this amounts to 0.08 feet per second. Since the TACAN wavelength $\approx$ 35 mm (0.115 feet), the period of a reinforcement/cancellation cycle is on the order of 1.4 seconds. The situation at South Lake Tahoe is believed to be similar to this. When the signal phases are in cancellation, then multipath reflections from other objects such as the surrounding mountains can cause lock-on giving a false range indication. As demonstrated in Section 4.3, this happened quite frequently. This could have been cured had the beacon been placed at some location with a much higher elevation.

The second beacon placement problem resulted from one of the beacons being placed in an unplanned location (the Meeks Bay location, MKB). Original plans called for a single beacon to be located further south (at Rubicon Point). When the time for beacon installation came, one was installed at Meeks Bay, and a second was installed further south at Emerald Bay (EMB), later in the day. The problem with the MKB location is that it is virtually colinear with two other beacons, LTA and LTT, and also the runway threshold. Because of this, when the aircraft nears the runway, if LTT is not being received, the other two beacons (LTA, MKB) cannot be counted on to give an accurate position measurement since the multilateration GDOP grows large. This created a considerable data reduction problem during the Loran-C accuracy analysis study. Later in the day when the EMB beacon was installed, this problem was relieved considerably.

In Figure 2.2 the beacon layout for Klamath Falls is illustrated. The same philosophy (airport beacon-Klamath VOR (LMT), off-course beacon (SPL) and third beacon (STM)) was followed. In this case two types of beacon placement problems arose. Due to the low elevation of SPL and the rolling terrain, that beacon was unusable during the final part of the approach (as was demonstrated in Section 4.3). The other problem was discussed in Section 4.1. There was some uncertainty in the knowledge of the exact location of the STM beacon.

In Figure 2.3 the beacon layout at Grand Junction is illustrated. At this site an airport beacon (designated FIR), an off course beacon (Grand Junction VOR (GJT)) and a third beacon (PER) were used. Good coverage was available from all three beacons, and few problems were encountered at data reduction time.

Figure 2.4 illustrates the beacon layout used for the Reno Airport shakedown flights. No attempt to optimize beacon layout here was made. Existing DME beacons at Reno VOR (RNO) and the Reno ILS DME (IRN) were tuned. The beacon at the Sierra-Nevada Corp. facility at Stead airport was used (called SNC). A beacon was located on the top of Peavine mountain (PVN). All locations were accurately known. Coverage from all beacons was relatively good. Shakedown flights were also performed at Reno Stead airport. For this test the Reno VOR(RNO), PVN and SNC locations were used. Also, a beacon (DRI) was located southwest of the airport on the roof of the University of Nevada Desert Research Institute. As before no attempts were made to optimize beacon layout. Reasonably good coverage was available from PVN and SNC and, to a lesser extent, DRI. Coverage from RNO was spotty due to the 10-15 mile range and intervening terrain.

After a review of the success rate of the beacon layout philosophy adopted, it may be concluded that it worked reasonably well. Even better results would have obtained if the philosophy had been adhered to rigidly (the most notable exception being the unplanned beacon location at South Lake Tahoe). The multipath interference problem with the airport beacon at South Lake Tahoe was unanticipated. It is apparent that the philosophy applied has at least one flaw, however. As the aircraft proceeds to the missed approach point, the GDOP relative to the airport beacon and off-course beacon deteriorates. If redundant coverage is not available, it becomes impossible to determine position accurately. This problem is very sensitive to the actual flight path of the aircraft. If the aircraft drifts off towards the off-course beacon side of the course line, the aircraft will actually fly through the baseline between the beacons, resulting in infinite GDOP. In order to overcome this problem, an alternative beacon geometry is suggested, as pictured in Figure 4.15.

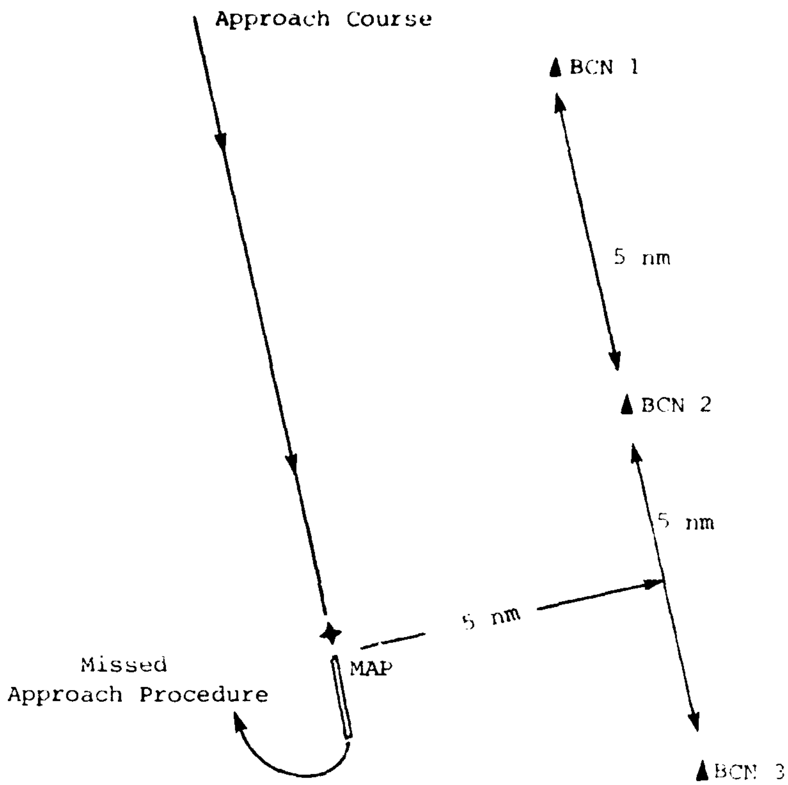


Figure 4.15 Suggested Beacon Layout

While an airport beacon is not shown, its existence would enhance overall system performance. The object of the layout shown is two-fold: The use of a beacon located before (#2) and after (#3) the Missed Approach Point assures good GDOP throughout the final part of the approach, even if one of the three beacons is not being received (any two of the three provide good GDOP). During the initial part of the approach the aircraft is typically at a higher altitude and can more easily receive all three beacons (as well as nearby VORs, if any exist). Also, if all three beacons are located on the same side of the approach course, the aircraft cannot cross the baseline between beacons and thus suffer unbounded GDOP. Finally, if in hilly terrain, it is advantageous to locate beacons on hillsides in clear view of the airport.

5.0 PERFORMANCE OF THE DATA COLLECTOR

This section covers the basic features and capabilities of the data collector unit of the RAPPS system. The data collector consisted of an Intel System 80 chassis and power supply, SBC-80 processor card, associated memory RAM and PROM card, interface port card and special wire-wrap card configured to interface to the DME/Channel scanner unit. Also included is a Tektronix 4051 intelligent graphic terminal, a Tektronix 4923 tape cartridge recorder, and a Tandberg SCDR-3000 tape cartridge recorder. The system was controlled by a PROM-resident software package. Communications with the operator is accomplished through the 4051 terminal.

5.1 TIMELINESS AND SUITABILITY OF THE DATA

The data stream collected and formatted for output by the SBC-80 system is documented in detail in the flight test report[1]. Included in the output data format are fields for each of the six DME measurements (one per channel tuned), one field for TDL-424 Loran-C receiver CDU (control-display unit) data (the TDL-424 was not installed during this test), four fields for TDL-711 CDU data, one field each for altitude and time (one second intervals), and one field for the TDL-711 RDU (remote-display unit) data stream (157 bytes of core-image data). All but the TDL-711 RDU data stream are illustrated in Figure 5.1. The entire buffer is initialized to character "1" after a record is output to the tape recorders (the RDU buffer is not so initialized). Data received replaces current buffer contents such that the buffer always contains the last data received before a data record is recorded. In the case of the DME data, positions are reserved for six successive channel scans. In the case of the Loran-C (TDL-711) data up to four of the possible maximum of six data records receivable in the 6-second cycle time are stored. In none of these cases are unique time identifiers associated with the individual data items. This does not create a serious problem in regard to the DME data since it is known that the most recent data is in the left-most DME position, and that it corresponds to the time-of-day recorded in the time position. The case of the Loran-C data is more

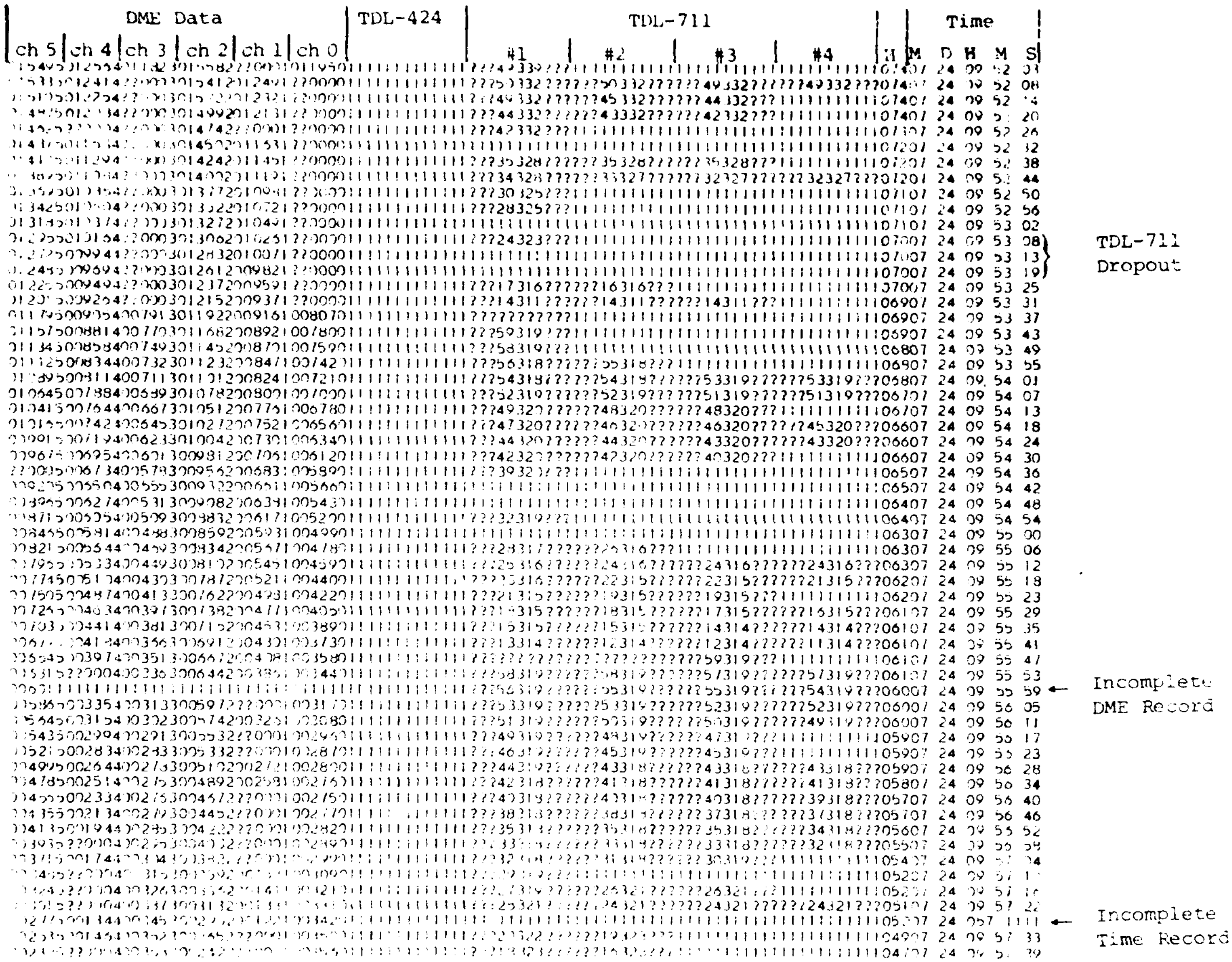


Figure 5.1 RAPPS Data Format With Data Collector Errors

problematic. Four, rather than six, positions were provided since the initial design cycle time of the DME channel selector was four seconds, not six, and since the CDU update interval was specified by the manufacturer to be one second. However, since the scan rate was later slowed to six seconds, and since the navigator is rather unpredictable regarding data transmission interval, anywhere from zero to four CDU data positions may actually be filled in a given data record. Therefore, it is impossible to affix definitive times to each of the data records received. The best information that can be derived is obtained by counting the number of records received. If, for example, two were received, it may be assumed that the second is no more than four seconds old. The RDU data field is replaced with each succeeding record received from the navigator. Thus its age is also unknown. Use was made of the known fact that CDU and RDU transmissions proceed in tandem, and so the count of received CDU updates can be used to estimate the probable age of the RDU data stream.

The data collection software exhibited a rather interesting "quirk" which resulted in data recovery and analysis problems. There is apparently an unresolved timing problem regarding loading of the data buffer with received data, and then outputing the resulting data to the recorder. This problem results in partially-filled fields in the data buffer. The most seriously affected fields were the DME measurements and time. Quite often the time field would be partially filled with "1" characters, or would contain the correct data in the wrong position. Likewise a DME position would contain the apparently-correct reading of 111.11 miles on channel 1, or a field partially filled with "1" characters and partially filled with correct data. No particular pattern which might indicate a cause and effect relationship has been observed. Figure 5.1 shows part of a printer dump of the data stream. Illustrated are occurrences of time field errors and DME field errors.

5.2 CONTROL-DISPLAY OPERATOR INTERACTIONS

Primary operator interface with the RAPPS package consists of the Tektronix 4051 graphic terminal, the System 80 reset switch, the DME channel selectors (thumbwheel switches) and the DME range acquisition

indicator lights (one light per channel). The system is operated using the SBC-80 PROM monitor capability. No operating system as such was used. Programs were stored in PROM, and were executed with monitor instructions. Programs provided included several test utilities which allowed dumps to be made to the terminal of critical inputs (DME ranges, TDL-424 CDU data, TDL-711 CDU data, altimeter data, clock). Programs to play back a tape post-flight, and to manipulate the tape drive in flight, were provided in addition to the main data acquisition program. The data acquisition program displayed part of the acquired data stream as it was being acquired, but provided no verification that recording of the data was proceeding. Programs were terminated using the reset switch. Verification of range acquisition of each of the six tuned DME channels was available to the operator through examination of range acquisition indicator lights (which extinguished when lock-on was achieved), and examination of the data displayed on the terminal.

For the most part there was little for the operator to do once the data acquisition program was running. The set up process, which was accomplished while airborne, involved turning on all equipment, setting the DME channel selectors to the desired stations, determining that range acquisitions were successful to all beacons, communicating by radio to the beacon operators to clear up acquisition problems, setting up the tape recorder, and initiating data acquisition. Even though little further activity was required, the set up process was totally manual and required intimate knowledge of the operation of all equipment in the package.

6.0 CONCLUSIONS

6.1 DATA ACQUISITION SYSTEM PERFORMANCE

The data acquisition system feature of the RAPPS package functioned essentially as planned (with the exception of deficiencies noted below) and provided very useful data during the West Coast Loran-C flight test program. Data was recorded continuously throughout the tests, and all data was recoverable. There was no problem regarding scale or resolution of the data, since all source data was already in a digital format.

A data record was recorded every six seconds, and fields within the records were not time tagged. This caused considerable problems in the data reduction process. A clock with millisecond resolution rather than one second resolution should have been utilized. Either data records should have been recorded much more often, or each data field should have been time tagged in some manner.

The data reduction techniques utilized here and in an earlier analysis [1] relied on a data tracking loop technique to estimate aircraft position. It would have been far more beneficial if some independent source of velocity data were available to feed the tracking filter. Sources of data could have included aircraft airspeed and heading, or the output of an inertial sensor system. These capabilities were not a part of the original design objectives of the system.

The data acquisition system contained some errors which caused periodic mishandling of data, such that incorrect data was recorded on the tape (there was no indication on the tape that the data was incorrect). The primary cause of this effect was probably due to a software timing problem whereby some fields would be incompletely filled at the time that the data buffer was dumped to the tape. These instances were quite evident to a human observer reviewing a data dump, but required elaborate software traps in the analysis programs to prevent their propagation into the results. A secondary problem was identified. On occasion a DME range very near zero would be recorded in an otherwise valid data channel. The cause was not determined.

6.2 RAPPS RANGE MEASUREMENT SYSTEM PERFORMANCE

Due to the above-mentioned data acquisition system problem (zero range measurements), large DME errors were detected in 16 out of the 5969 DME readings evaluated (0.27% of measurements).

As a result of multipath effects and other ranging problems, a total of 100 moderate (greater than 1000 ft.) DME errors out of 5969 readings evaluated were isolated (1.68% of measurements). These were particularly prevalent in circumstances conducive to multipath problems; e.g. when ranging over the horizon or in the presence of a large, smooth body of water.

After filtering out the larger errors noted above, a residual ranging error of 285 ft. (1σ) for all beacons and locations was calculated as a result of the data evaluation performed in this study. It is believed that this number is very conservative (high relative to the actual performance of the system) due to the techniques which had to be used to estimate ranging error in the absence of a precision tracking range for evaluating DME performance. The α-β tracker algorithm can be thought of as a precise position standard with a relatively large additive, low-frequency noise source (which is essentially uncorrelated with the DME errors). If the uncorrelative assumption is valid, then the "tracker noise", which is of unknown magnitude, would be expressed as an increase in the DME error statistic. Thus the statistic is conservative.

The 285 foot error figure stated above is raw ranging system error, not positioning (X, Y) system error. The error experienced upon converting the ranges to positions through multilateration is totally dependent on two factors: aircraft/beacon geometry and the number of beacons supplying range data. Given good geometry and several beacons, the resulting position errors may be considerably better than the raw ranging error statistic.

Due to the frequency band of the ranging system, it exhibited a characteristic (which was fully expected) which requires careful test planning to avoid: range acquisition can be severely limited by terrain masking, multipath effects and aircraft altitude. These factors, as well as erroneous measurements which result from multipath during marginal range acquisition conditions cannot be overcome simply by locating more beacons in the test area, since they cause data reduction problems irregardless. All beacon site locations deserve serious planning and scrutiny.

In planning beacon layouts for a test environment, the coverage geometry of the beacon layout is of paramount importance. Beacon range is not a limitation (up to 40 miles for the Vega beacons). Coverage geometry should be evaluated relative to all parts of the intended flight path for which data is desired. Planning should also consider in each case an exact strategy for accurately determining the position of each beacon. Wherever possible, a plan should be defined to determine the ranging bias of all permanent TACAN or DME installations to be utilized. A successful flight test is highly dependent on the amount and quality of planning that precedes the test itself.

REFERENCES

1. Scalise, T.E., Bolz, E.H., McConkey, E.D., "West Coast Loran-C Flight Test", Systems Control, Inc.(Vt.), March 1980, FAA-RD-80-28.

2. "Final Technical Report, Remote Area Precision Positioning System, Phase I", Sierra Nevada Corp., Amex Systems, Inc., December 1979.

APPENDIX A

LORAN/DME FILTER MODEL

This appendix briefly describes the methods used to process the Loran-C and DME data recorded during the West Coast Loran-C Flight Test for purposes of analyzing the performance of the RAPPS ranging system. The basic processing technique utilized is the widely-known α, β tracker technique. This is basically a digitally-implemented servo loop expressed as a second order filter. The equations of the tracker and of the optimally-derived gains appear in detail in Reference 1. They are not repeated here. The model treats the aircraft dynamics as having independent characteristics in the longitudinal and transverse directions (relative to aircraft heading). Two gains are required for each channel (longitudinal and transverse): the position gain (α) and the velocity gain (β). These gains may be time-varying.

In Reference 1 the α, β tracker was used to track the DME data in X, Y coordinates and fixed gains were used. In the present analysis the tracker was used to track Loran-C data which had been converted (see Section 4.2) to X, Y coordinates. A set of fixed gains was derived but gains at any time were selected from that set based on the probable age of the last Loran-C data point received. These gains were derived based on assumptions which were formulated from experience in working with the data.

Assumptions

a) Typical ground speed = 140 kt.

b) Standard Deviation of Loran-C measurement error in X, Y coordinates = 0.04 nm.

c) Standard Deviation of transverse acceleration= 0.001 nm/sec^2.

d) Standard Deviation of longitudinal acceleration=0.00025 nm/sec^2.

e) Update Interval = 6 sec.

f) The probable age of the last received Loran-C update lies in an interval of time equal to six seconds (data frame interval) divided by the number of Loran-C updates known to be received in the frame. The distribution is assumed uniform so that the standard deviation = $\frac{1}{2} \cdot \frac{\sqrt{3}}{2}$. (the width of the interval in seconds).

Based on assumption b and f and the further assumption that those two error sources are independent and can be combined in an RSS fashion, the following table of Loran-C measurement accuracies (in nm) was derived:

Known Loran-C Updates Received in Data Frame	Width of Probable Loran-C Update Age Interval	Loran-C Measurement Error Result (Standard Deviation)
0	——	——
1	6 sec.	.109 nm
2	3	.064
3	2	.052
4	1.5	.047

Utilizing the equations of Reference 1 which relate α, β tracker optimal gain to the above-stated factors, the following table of filter gains results. The terminology is as follows:

α = position gain

β = velocity gain

Subscript T = transverse channel

Subscript L = longitudinal channel

Based on the contents of each frame of Loran-C data, the filter gains were adjusted to one of the five sets of values shown below as a function of the known received Loran-C updates counted in the data frame.

Known Loran-C Updates Recieved in Data Frame	Filter Gains (Dimensionless)			
	α_T	β_T	α_L	β_L
0	0	0	0	0
1	.554	.037	.333	.011
2	.650	.055	.411	.018
3	.687	.064	.444	.021
4	.704	.069	.460	.023

In addition to utilizing the α, β tracker as described, the Loran-C data values were inspected prior to use. Differences between predicted Loran position and received data of greater than 0.25 nm were limited to 0.25 nm in order to mitigate the influence of occasional outliers.

As stated in the main text (Section 4.2) the tracker performed reasonably well, but was not sufficiently consistent to allow proper evaluation of the DME data. This resulted primarily from the erratic update rate of the Loran-C data itself. There was nothing to indicate that the Loran-C data, when present, was not highly accurate. To improve the performance of the tracker algorithm, it was decided to inject the DME data itself in the process. Since the objective was to evaluate the DME data, this had to be done with care. To utilize the DME data, two things had to be done: first, the Loran-C bias in X and Y had to be estimated. Second, the DME data had to contribute to the tracker smoothing equations. Stringent limits were used to prevent potentially erroneous data (either Loran-C or DME) from contaminating the estimation process:

a) If the magnitude of a DME measurement error component (component of difference between measured DME range and range to beacon based on estimated position) exceeded 0.1 nm it was limited to 0.1 nm.

b) The estimate of Loran-C X, Y biases was only allowed to be updated during times when Loran-C data was self-consistent; i.e., when the total Loran-C measurement error (vector difference between measured Loran-C position and estimated position) was less than 0.1 nm, and when three or more Loran-C updates were received during a data frame.

The gains for the DME data were set to the highest Loran-C gains (four updates received during a data frame) times a parameter. The filter functioned by summing the X and Y components of the DME measurement errors found during a data frame (maximum of six). These sums were then included in the filter utilizing the gains mentioned above at each update interval (six seconds). The DME measurement errors also updated

the Loran-C bias estimate (under the restrictions of item (b) above) using a first order filter whose gain was also a parameter. These two parameters (tracker DME gain and Loran-C bias DME gain) were varied in a series of trial runs over several of the Loran-C approaches flown during the test. The behavior of the resulting system was judged based on the following subjective criteria:

a) Stability of the Loran-C biases

b) Response to aircraft dynamics, including rapid convergence on new heading/airspeed without overshoot

c) Ability to minimize the number of falsely-identified significant DME ranging errors.

After many trials the following values were selected:

Tracker DME gain parameter = 75%

Loran-C bias DME gain parameter = 0.025

With this configuration the entire system performed very well, although it was still necessary to manually identify times of high dynamics (turns) to prevent false identification of significant DME ranging errors. Data during turns was eliminated from the ranging error analysis.